NOTE

This Microfiche meets the quality requirements of the American National Standard for Microfiche of Documents (ANSI PH5.9-1975). However, because of imperfections in the document from which it was made, it contains images that are illegible or difficult to read. The source document for this microfiche is the best copy that could be obtained prior to filming.

CIS

Congressional Information Service, Inc.
Washington, D.C.

THE POTENTIAL FOR NEW METAL PROCESSING TECHNOLOGIES TO REDUCE CONSUMPTION OF CRITICAL METALS

Submitted by
Charles River Associates

December 30, 1983

Submitted to the

Office of Technology Assessment
Congress of the United States
Washington, D.C. 20510

"These Working Papers were prepared by outside contractors as an input to an ongoing OTA Assessment. They do not necessarily reflect the analytical findings of OTA. These Working Papers have been neither reviewed nor approved by the Technology Assessment Board."

J952-54

Charles
River
Associates

Final Report

NEW METALS PROCESSING TECHNOLOGIES

Prepared for

The Office of Technology Assessment
The Congress of the United States
Washington, D.C. 20003

CRA Report No. 741

Prepared by

Charles River Associates Incorporated
200 Clarendon Street
Boston, Massachusetts 02116

December 1983

"This is an OTA Working Paper that was used in preparing OTA's final Assessment Report on Strategic Materials: Technologies to Reduce U.S. Import Vulnerability. OTA makes these Working Papers available for the use of readers desiring a more detailed or technical discussion of an issue than can normally be accommodated in our final Report. As an OTA Working Paper, this report has not been reviewed or approved by the Technology Assessment Board. The findings and conclusions expressed in the report are those of the authors and do not necessarily reflect the views of OTA, the Strategic Materials Advisory Panel, or the Technology Assessment Board."

CRA

TABLE OF CONTENTS

Page

Chapter 1. EXECUTIVE SUMMARY: SUMMARY OF TECHNOLOGICAL CHANGES AND THEIR IMPACT ON MATERIALS NEEDS 1

Chapter 2. PRIMER ON METALS PROCESSING TECHNOLOGY. 4

- Introduction 4
- Current Metals Processing Technologies 4
- Materials Used in Fabrication. 5
- Forming and Treating Processes 7
- Steel Processing 9
  - The AOD Process for Stainless Steel 11
  - Possibilities for Chromium Conservation and Substitution in the AOD 17
- Continuous Casting 20
- Advanced Melting Technology. 20
- Forging Technology 26
- Powder Metallurgy Techniques 31
  - Hot Isostatic Pressing. 33
  - Cold Isostatic Pressing 33
  - Rapid Solidification. 33
  - Precision Casting 37
  - Surface Modification. 41
  - Coatings. 43
  - Ion Implantation. 45
  - Cladding. 46
  - Future Advances in Metal Processing Technology. 47
- Summary. 55

Chapter 3. SPECIFIC END-USE APPLICATIONS 58

- General Introduction 58
- Gas Turbine Engines. 62
  - Introduction. 62
  - Casting Technologies. 63
  - Forging 66
  - Powder Metallurgy Technologies. 67
  - Superplastic Forming/Diffusion Bonding. 70
  - Dual Materials. 71
  - Summary and Conclusions 71
  - Non-Technical Issues. 72
- Oil Country Tubular Goods for Deep Sour Gas Wells. 72
  - Materials Selection 73

TABLE OF CONTENTS (Continued)

Page

Steel Plate in Heavy Equipment and Construction. 75
  External Desulfurization. 78
  Lowering the Manganese-to-Sulfur Ratio. 78
  Primary Steelmaking 79
  Ladle and Secondary Refining. 80
  Continuous Casting. 80
  Conclusion. 80
Summary and Conclusions. 81

Chapter 4. TECHNICAL, ECONOMIC, AND INSTITUTIONAL FACTORS. 83

Technical Barriers 83
  Forging Technology. 84
  Precision Casting 85
  Powder Metallurgy 86
  Surface Modification, Coatings, and Cladding. 88
  Scrap Recycling 88
Economic Benefits of New Processing Technologies 89
  Forging 89
Institutional Barriers 98
Summary of Research and Development Activities 100
  University Programs 102
  Corporate R&D 102

Chapter 5. PROJECTED USE OF NEW TECHNOLOGIES BY END USE. 105

Chapter 6. THE STATUS OF UNITED STATES VERSUS FOREIGN TECHNOLOGY . . 109

LIST OF FIGURES

Page

Figure 2-1. MATERIALS FLOW CHART 8
Figure 2-2. SCHEMATIC ELEVATION SHOWING THE RELATIVE LOCATIONS OF VARIOUS OPERATING UNITS OF THE BASIC OXYGEN PROCESS STEELMAKING SHOP 10
Figure 2-3. SCHEMATIC CROSS-SECTION OF A HEROULT ELECTRIC-ARC FURNACE. 12
Figure 2-4. SEQUENCE OF ARGON-OXYGEN VESSEL OPERATION FOR STAINLESS STEEL. 14
Figure 2-5. FLOW SHEETS INDICATING GENERAL PRINCIPAL STEPS IN THE PRODUCTION OF STAINLESS STEEL PRODUCTS. 19
Figure 2-6. SCHEMATIC DIAGRAM DEPICTING HOW LIQUID METAL PERSISTS IN THE CENTER OF A CONTINUOUS CASTING FOR A CONSIDERABLE DISTANCE AFTER THE CASTING LEAVES THE WATER-COOLED MOLD, FORMING A SO-CALLED "CRATER". . . 21
Figure 2-7. SCHEMATIC VERTICAL CROSS-SECTION OF THE GARY WORKS SLAB CASTER, SHOWING THE RELATIVE LOCATIONS OF THE SUCCESSIVE OPERATING UNITS 22
Figure 2-8. PRINCIPAL CONSUMABLE ELECTRODE REMELTING SYSTEMS 24
Figure 2-9. PRINCIPLES OF SEVERAL TYPES OF FORGING OPERATIONS. . . . 27
Figure 2-10. FORWARD EXTRUSION, (A); BACKWARD EXTRUSION, (B); TUBE EXTRUSION, (C); AND CONTAINER EXTRUSION, (D). . . . 28
Figure 2-11. SCHEMATIC OF GATORIZING FORGING APPARATUS. 32
Figure 2-12. FLOW DIAGRAM FOR HOT ISOSTATIC PRESSING. 34
Figure 2-13. SCHEMATIC OF CENTRIFUGAL ATOMIZER SHOWING THE ARRANGEMENT FOR HIGH MASS FLOW GAS QUENCHING - RSR PROCESS. 36
Figure 2-14. GRAPHITE DIRECTIONAL SOLIDIFICATION FURNACE. 39
Figure 2-15. DIRECTIONAL SOLIDIFICATION AND SINGLE CRYSTAL CASTING. 40
Figure 2-16. SCHEMATIC OF THE "LAYERGLAZE" PROCESS. 42
Figure 2-17. DIFFERENT ENVELOPES ASSOCIATED WITH DIFFERENT FORGING PROCESSES. 52
Figure 2-18. ALTERNATIVE PROCESSING ROUTES FOR VIM INGOTS 56

Figure 4-1. ISOTHERMAL FORGING IMPROVEMENTS OVER CONVENTIONAL FORGINGS. 91
Figure 4-2. COMPARATIVE MANUFACTURING PROCESSES FOR MAKING A SUPERALLOY TURBINE ENGINE SHAFT. 96
Figure 4-3. RELATIVE COSTS OF FORMING PROCESSES: HIP VERSUS FORGING FOR A COMPRESSOR WHEEL 97

LIST OF TABLES

Page

Table 2-1. COMPOSITIONS OF IMPORTANT ALLOY TYPES CONTAINING CHROMIUM, COBALT, AND MANGANESE. 6

Table 3-1. U.S. COBALT CONSUMPTION BY USE IN 1980. 59
Table 3-2. U.S. CHROMIUM CONSUMPTION BY END USE IN 1980. 60
Table 3-3. U.S. MANGANESE CONSUMPTION BY END USE IN 1980 61

Table 4-1. ENGINE BUY/FLY MATERIAL BREAKDOWN FOR PRATT AND WHITNEY JT94 JET ENGINE 90
Table 4-2. BLANK FABRICATION LEVEL COSTS FOR A Ti-6242Si DISK. . . . 93
Table 4-3. MANUFACTURING LEVEL COSTS FOR A Ti-6242Si DISK. 94

Table 5-1. FUTURE SAVINGS OF CHROMIUM, COBALT, AND MANGANESE FROM THE USE OF NEW FABRICATION TECHNOLOGY, FOR 10-YEAR AND 25-YEAR PROCESSES 107

1

EXECUTIVE SUMMARY: SUMMARY OF TECHNOLOGICAL CHANGES AND THEIR IMPACT ON MATERIALS NEEDS

This report assesses new processing and fabrication technologies for metals that have either recently reached commercialization or are still being developed. The study's overall goal was to examine the impact these technologies will have on the conservation of such critical metals as cobalt, chromium, and manganese. The report describes the new technologies and evaluates their impacts on the use of chromium, cobalt and manganese in three specific end-use applications: gas turbines, oil country deep sour gas wells, and constructional steel. The report examines the overall technical, economic, and institutional factors that will influence expansion in the use of new molding, forging, casting, powder metallurgy, and surface modification technologies.

In aerospace applications such as gas turbine engines, it is expected that through process advances, overall cobalt and chromium savings will amount to 10 to 12 percent of present usage in input raw material by the early 1990s and over 25 percent by early next century.

Chromium use in oil country goods has begun to expand, in an overall oil country product market that could reach $600 million by the late 1980s. But cladding of plain steel with superalloys having the same corrosion-resistance as solid superalloy tubulars could limit the growth in demand for chromium, since claddings would use only 10 or 20 percent of the chromium.

Finally, process changes in basic steelmaking and fabrication are expected to reduce future requirements for manganese by 30 percent in the next 10 years, and possibly by 40 percent in 25 years. These changes include better control of sulfur, improved oxygen blowing techniques in the basic oxygen process, improved process controls in the AOD process for stainless steel, ladle refining, phasing out of open hearths, and continuous casting.

Current state-of-the-art technology, largely developed for jet engine part fabrication, is expected eventually to filter down to such industrial applications as chemical processing and motor vehicles. Superalloy usage is spreading to nonaerospace applications such as oil country tubular goods, military equipment, heavy-duty tooling, waste incineration, glass manufacture, heat recuperators, auto/diesel engine parts, flue gas desulfurization, marine hardware, pulp and paper production, medical and dental uses, and nuclear processing. The new technologies are likely to diffuse into these end uses as performance and cost-effectiveness criteria continue to be emphasized. The new forging, casting, powder metallurgy, and coating technologies could reduce the use of chromium, cobalt and manganese in these other applications by between 10 to 25 percent of today's base levels.

The current goal of fabricators is to produce cleaner metal, more free of impurities, by optimization of vacuum melting and refining technology. Nondestructive testing methods must be developed to quality test to net shape size and to reduce the current size of the material envelope around parts that is required for testing. Isothermal forging, hot die forging, precision casting (directional solidification and single-crystal casting) and hot isostatic pressing form the key technology base from which future advances will be made.

Potential savings in materials and costs range from 20 to 50 percent, depending on the application. In aerospace applications, buy-to-fly ratios have been reduced from an average of 5 or 6 to as little as 1 to 1.2 or 2 to 1 for some particular parts. Most jet engine manufacturers are participating in this kind of improvement in making certain parts.

Surface modifications in the form of laser treatments, ion implantation, and various coatings and claddings will have a major impact on future requirements for critical metals, since they can provide excellent wear- and corrosion-resistance and use only 5 to 10 percent of the former quantities of critical elements. In the area of joining, superplastic-forming and diffusion-bonding are broadening their applicability from aerospace uses and will eliminate the need for fasteners in many areas. Large precision castings are also likely to be incorporated into automotive and off-highway vehicle areas in the future, and this will make it possible to produce entire assemblies as one part, thereby eliminating welding, joining and fastening in certain applications.

Automation, along with computerized sensing and control, will continue to be emphasized with a view to increasing throughput rates and precision parts; these advances will translate into lower costs and higher yields and efficiencies, particularly in foundries and in the vacuum melting of superalloys.

Designers still express some preference for materials made by technologies with which they are comfortable, although in aerospace applications there is a greater tendency than in other industries to use new technologies because of the aggressive drive in this industry for higher performance and cost savings. EPA regulations on metal sludge and acid disposal are contributing significantly to the cost of producing parts, but at the same time are providing incentives to develop recycling technology as a less costly alternative to disposal. Competition from abroad in the form of imports and cooperative technology agreements as well as more stringent quality controls are compelling U.S. companies to push toward higher quality and lower fabrication costs to preserve U.S. competitiveness in world markets.

2

PRIMER ON METALS PROCESSING TECHNOLOGY

INTRODUCTION

This primer is intended to familiarize the reader of this report with the existing processing and fabrication technologies that are currently in use for the production of parts made from stainless steel, superalloys, and other alloys containing chromium, cobalt, and manganese. While the report itself will discuss in more detail the various elements of these technologies as well as their associated technical barriers, potential advantages, disadvantages, and economic benefits, this primer will provide an overview of the processes used in producing a finished part out of metal raw material.

The emphasis in this primer is on the section of the process flowsheet that begins with the metal raw material, either as a pure molten form (in preparation for casting), as a raw billet (in preparation for forging), or as a metal powder (in preparation for pressing and sintering). We briefly discuss the processing steps involved in melting and production of the proper molten metal alloy to be used as the raw material for fabrication.

Savings in material usage cited in this report refer to input raw material before it passes through the fabrication process and not to savings in consumption at the final part stage.

CURRENT METALS PROCESSING TECHNOLOGIES

Current technologies for processing metals, beyond the primary extractive metallurgical recovery from ore, are quite similar for the alloys under consideration in this study, namely the nickel- and cobalt-base superalloys, stainless steels and heat-resistant alloys, full-alloy steels, tool steels, and low-alloy steels. Typically, the metal is taken from primary recovery in its molten form and from this stage can be treated in several ways. The metal is usually cast into ingots and then made into billets. These billets can be subsequently rolled or forged into parts, remelted and alloyed for casting parts, or rolled into wrought products such as plate, sheet, strip, pipe, rod, and bar. Some of these mill products serve as basic forging stock, such as rod and bar, to be forged into finished parts. Alternatively, metal powders can be produced from the molten or solidified state for subsequent forming into solid metal parts.

MATERIALS USED IN FABRICATION

The important alloys that contain chromium, cobalt, and manganese are listed in Table 2-1, which shows the typical compositions of the different alloys. Manganese is an alloying element that is common to essentially all specialty steels, first because of its effect in reducing sulfur in the molten metal and changing the shape of sulfides (thereby counteracting the hot-shortness problem that causes cracking in the cast billets), and second because of its effect on increasing the hardening of the alloy during subsequent processing operations. The chromium is added to several classes of alloy steels at the 1 to 2 percent level primarily as a hardener because it is one of the strongest carbide-forming elements available. These strong chromium carbides also resist resolution (or dissolving) back into the matrix at higher temperatures, imparting high-temperature strength to the alloys.

Alloy steels are used to achieve strength, wear-resistance, and hardenability improvements over carbon steels. Alloy steels typically have two to four times the tensile strength of carbon steels; they are chosen when parts are highly stressed and must have dependability over a long service life. In chromium concentrations above 12 percent,* the alloys become stainless, corrosion-resisting alloys; the chromium acts primarily as the key element in forming the strong passivating oxide skin on the steel that resists corrosive attack. In tool steels, the main characteristics are wear-resistance and extreme hardness for cutting and machining metal parts. These steels have high levels of strong carbide-forming elements such as chromium, molybdenum, tungsten, and vanadium for imparting high hardness to the steels. Cobalt is present in most grades because it prevents softening at elevated temperatures; in other words, it improves what is called the hot hardness of the steel.

The nickel- and cobalt-base superalloys are defined as those alloys that must have high strength and corrosion resistance at elevated temperatures. Most have less than 50 percent iron content versus the stainless steels which typically have over 50 percent iron. Certain so-called superstainlesses possess high levels of chromium and nickel and sometimes molybdenum but still

---

*It is generally accepted that 12 percent chromium content is the threshold level for significant corrosion resistance, although some alloys with below 11 or 12 percent chromium are still denoted as stainless steels.

Table 2-1

COMPOSITIONS OF IMPORTANT ALLOY TYPES
CONTAINING CHROMIUM, COBALT, AND MANGANESE

Alloy Type	Percent by Weight					
	Cr	Mn	Co	Ni	Fe	C
Full-Alloy Steel	0.4-1	0.6-1	--	.35-4	bal	.15-5
Low-Alloy Steel	0.3	0.6-1	--	--	bal	.05-1
Stainless Steel	12-18	1-2	--	0-8	bal	.08
Tool Steel	4.0	--	5-12	--	bal	1.0
Ni-base Superalloys	20	0-1	10-15*	bal	3-5	.05-1
Co-base Superalloys	20	0-1	35-50	10-20	3	.1-1.0

*Some nickel-base superalloys have 0 to 2 percent cobalt, such as the common INCO 718 and some of the Hastelloys.

SOURCES: Metal Progress, 1982 Databook; AISI Standard Steels, 1977.

are iron-based and do not have the elevated temperature strength and corrosion performance of superalloys. The nickel-base alloys offer the highest strength for rotating parts in jet engines, such as compressor disks, and the cobalt-base alloys tend to offer very high temperature creep-resistance (i.e., slow deformation under stresses at elevated temperatures). Cobalt-base alloys have been used for turbine engine blades and vanes that must withstand the hottest and most corrosive environments. The cobalt contents in the nickel-base alloys average about 10 to 15 percent; however, newer alloys have been commercialized with 0 to 2 percent cobalt content. These superalloys are used in jet engines and industrial gas turbine engines, and, because of their outstanding corrosion-resistance, are being found increasingly cost-effective for use in the chemical processing and pharmaceutical industries, in pulp and paper production, and in forming pipe casings for deep, high-sulfur gas well drilling. The quality specifications of the superalloys will be different for aerospace versus nonaerospace uses. Some aerospace-quality alloys may be used in nonaerospace uses, but usually the alloys will have less stringent quality control processes in production. For example, nickel-base Alloy 718 for rotating parts in a jet engine will be produced to more rigorous standards than Alloy 718 for oil country tubular goods.

FORMING AND TREATING PROCESSES

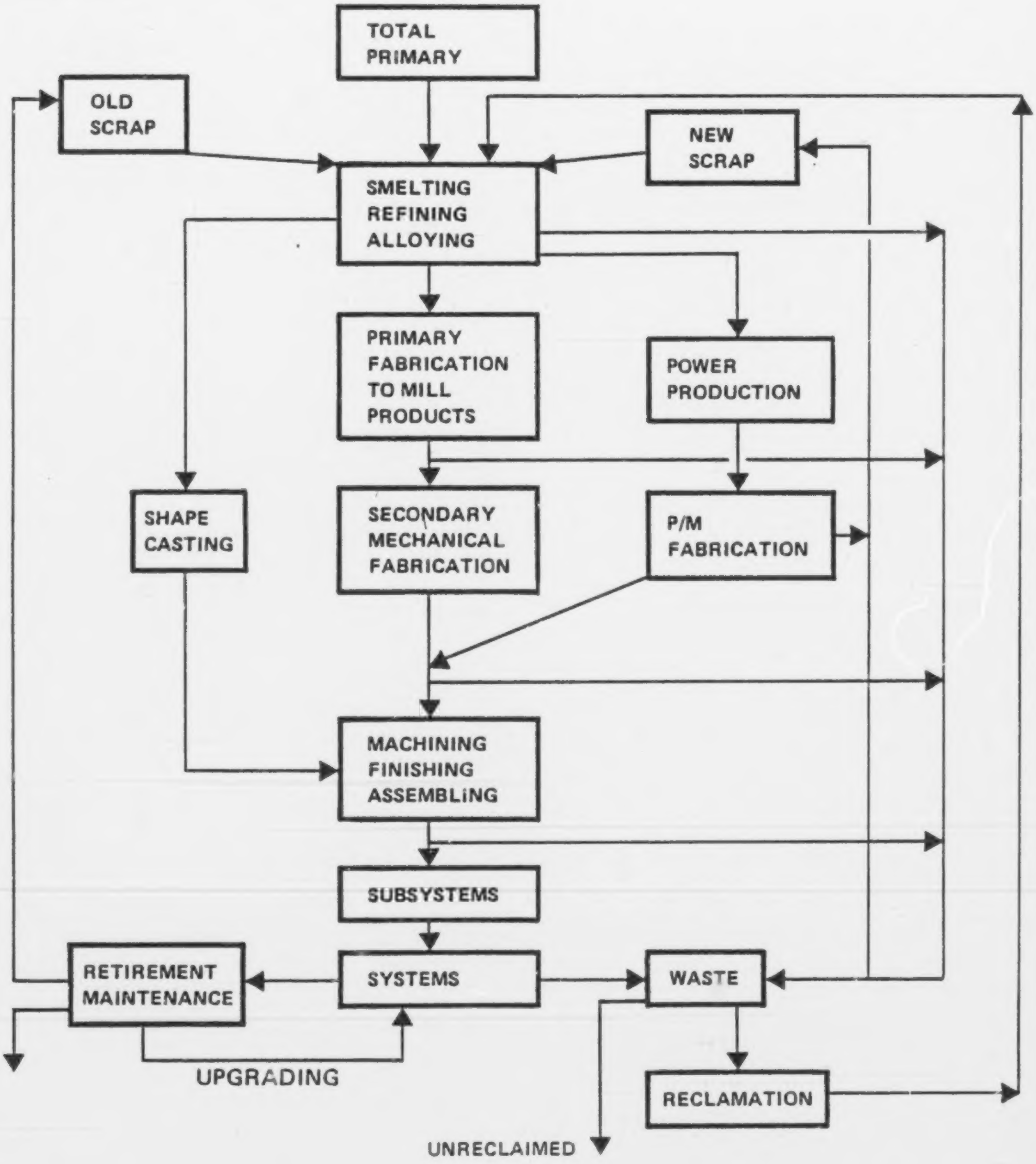
The steps in the fabrication of finished products from each type of alloy product are shown in a materials flowchart in Figure 2-1. All the alloys follow the basic sequence of steps shown in this figure, from the input of raw materials through smelting, refining, and alloying to desired specification in the furnace. From this stage, the molten alloy is cast into ingots and fabricated by rolling mills into primary mill products with attendant scrap generation due to oxidation and scaling off of the metal surface. The products from primary fabrication typically consist of blooms, billets, bars, rod, plate, sheet, and strip. Secondary fabrication is required to provide further finishing. This may consist of further rolling and furnace heat treating operations to produce specific gauges of sheet, plate, or shapes.

Forging is used for many products, such as parts for jet engines, automobiles, and off-highway vehicles. Forging is essentially a controlled deformation performed on a piece of metal stock to bring it near its final part shape, after which machining finishes the part to final tolerances. Scrap is generated from the forging operation in the form of forging flash, the extra metal that extrudes from the forging dies; this requires removal in a separate step. Flash averages 20 to 40 percent of the original workpiece. Machining again generates additional scrap in the form of chips and turnings that are usually saved for recycling.

Parts may also be conventionally cast or precision-cast and finish-machined, or parts may be consolidated from alloy powders. These techniques typically generate less scrap than forging, but some material is scrapped in both types of operation.

Figure 2–1

MATERIALS FLOW CHART


TOTAL PRIMARY
OLD SCRAP
NEW SCRAP
SMELTING REFINING ALLOYING
PRIMARY FABRICATION TO MILL PRODUCTS
POWER PRODUCTION
SHAPE CASTING
SECONDARY MECHANICAL FABRICATION
P/M FABRICATION
MACHINING FINISHING ASSEMBLING
SUBSYSTEMS
RETIREMENT MAINTENANCE
SYSTEMS
WASTE
UPGRADING
RECLAMATION
UNRECLAIMED

SOURCE: Charles River Associates, 1983.

Finally, old scrap is recovered from worn-out parts, some of which can be recovered during maintenance operations and fed back into the cycle as part of the new melting charge for producing new alloy.

Analysis of the effects of new fabrication technologies on reducing scrap generation and losses is complex because scrap is usually a part of every alloy melting heat, and if scrap availability is reduced, there are increased requirements for primary metal to make up the lack. There is a tradeoff between the cost of using more primary input and the cost of scrap recovery.

Following this background to the general materials processes, the next section focuses on the main fabricating techniques used today as well as potential advances likely to be made in the future.

STEEL PROCESSING

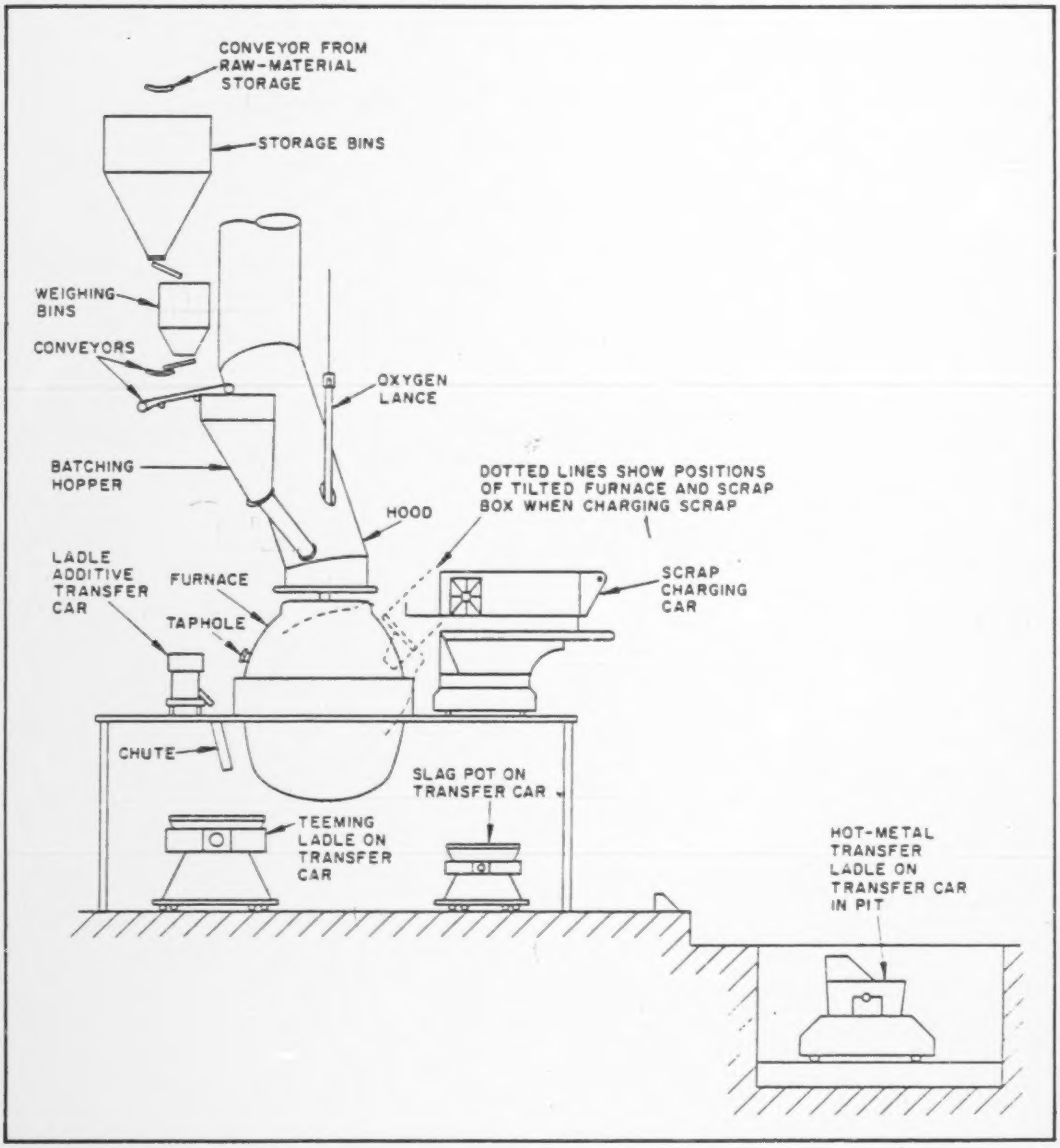
Currently, the most common processes for making steel from iron ore are the Basic Oxygen Furnace (BOF) Process and the Electric Arc Furnace (EAF) Process for alloy and carbon steels and the Argon Oxygen Decarburization (AOD) process for stainless steel. These steelmaking processes have become dominant because of their speed of refining, economy of labor, ease of fume control (for the BOF), high-quality products, promise of full automation, and regularity of the production cycle.

Of the total 121 million tons of all grades of steel produced in the United States in 1981, 60.6 percent was generated by the Basic Oxygen Process and 28.3 percent by the Electric Arc Furnace Process (including the AOD). The remainder was produced in the older, slower, and more costly Open Hearth Process, which has been declining in use for about 15 years and which is expected gradually to be phased out completely.

The Basic Oxygen Furnace (BOF) is a vertical solid-bottom crucible with a vertical water-cooled oxygen lance entering the vessel from above through which oxygen is blown into the charge at high pressure to oxidize impurities and lower the carbon level. The vessel is tiltable for charging and tapping. The charge is normally made up of molten pig iron ("hot metal"), scrap, and fluxes. Small quantities of cold pig iron and iron ore may also be charged. The distinguishing feature of the BOF is that the heat produced by reaction of the oxygen with various constituents of the charge is used without other sources of energy except carbon to bring the metal to its desired final conditions of composition and temperature. Occasionally, the heat balance may be altered by the introduction of supplementary fuel to permit melting above-normal amounts of scrap. A unique aspect of the operation is that the energy generated during refining may be predicted with reasonable accuracy. Thus, the heat may be "programmed" to a desired end-point carbon content and temperature (within the accuracy of the input data and the control model). The furnace set-up is illustrated in Figure 2-2. The BOF is used to make carbon steels and alloy steels, but not stainless steel or tool steel.

Figure 2–2

SCHEMATIC ELEVATION SHOWING THE RELATIVE LOCATIONS OF VARIOUS OPERATING UNITS OF THE BASIC OXYGEN PROCESS STEELMAKING SHOP


CONVEYOR FROM RAW-MATERIAL STORAGE
STORAGE BINS
WEIGHING BINS
CONVEYORS
OXYGEN LANCE
BATCHING HOPPER
DOTTED LINES SHOW POSITIONS OF TILTED FURNACE AND SCRAP BOX WHEN CHARGING SCRAP
HOOD
LADLE ADDITIVE TRANSFER CAR
FURNACE
TAPHOLE
SCRAP CHARGING CAR
CHUTE
SLAG POT ON TRANSFER CAR
TEEMING LADLE ON TRANSFER CAR
HOT-METAL TRANSFER LADLE ON TRANSFER CAR IN PIT

SOURCE: *The Making, Shaping and Treating of Steel*, U.S. Steel Corporation. 1971.

The Electric Arc Furnace technique utilizes the heat from an electric arc to melt the charge. The arc heating may be applied in two ways: 1) the arcs may pass between electrodes supported in the furnace above the metal, with heating thus occurring solely by radiation; or 2) the arc passes from one electrode into the metal charge and back to another electrode, thereby developing heat by the metal's electrical resistance as well as by radiation.

Figure 2-3 illustrates a typical electric arc furnace design. The furnace charge is in the trough in the bottom center of the diagram and the special graphite electrodes are slid down close to the metal.

Electric arc furnaces can make essentially any steel product, from carbon steel and alloy steel to stainless steel, tool steel, and other more specialized steel types. The process is quite flexible, since it can handle almost any type of charge, particularly an all-scrap charge, and it can operate economically on an intermittent basis. The electric arc process allows control over steel composition in various ways. Control over unwanted residual phosphorus and sulfur is superior to that in other processes because the initial charge contains less of these elements than an all-blast furnace iron charge. Since the process operates under reducing conditions rather than oxidizing conditions, the reducing slag has greater desulfurizing power. Phosphorus-bearing slags may be readily removed before any reoxidizing and reversion back to the melt take place. The reducing slag condition allows better control and recovery of alloying elements in the metal, since there is less tendency for alloying metals to oxidize and end up in the slag. This is particularly important for chromium, manganese, and other readily-oxidizable elements (such as molybdenum and vanadium). The definite regulation of heat input through the electric arc provides good control of the carbon level. Again, because of the reducing conditions of the slag, fewer final deoxidizing agents (to remove oxygen from the molten metal) have to be added, thereby lowering costs. As a result of these factors, steel produced in electric arc furnaces has fewer sulfide and oxide inclusions, which can severely limit the formability and properties of the steel.

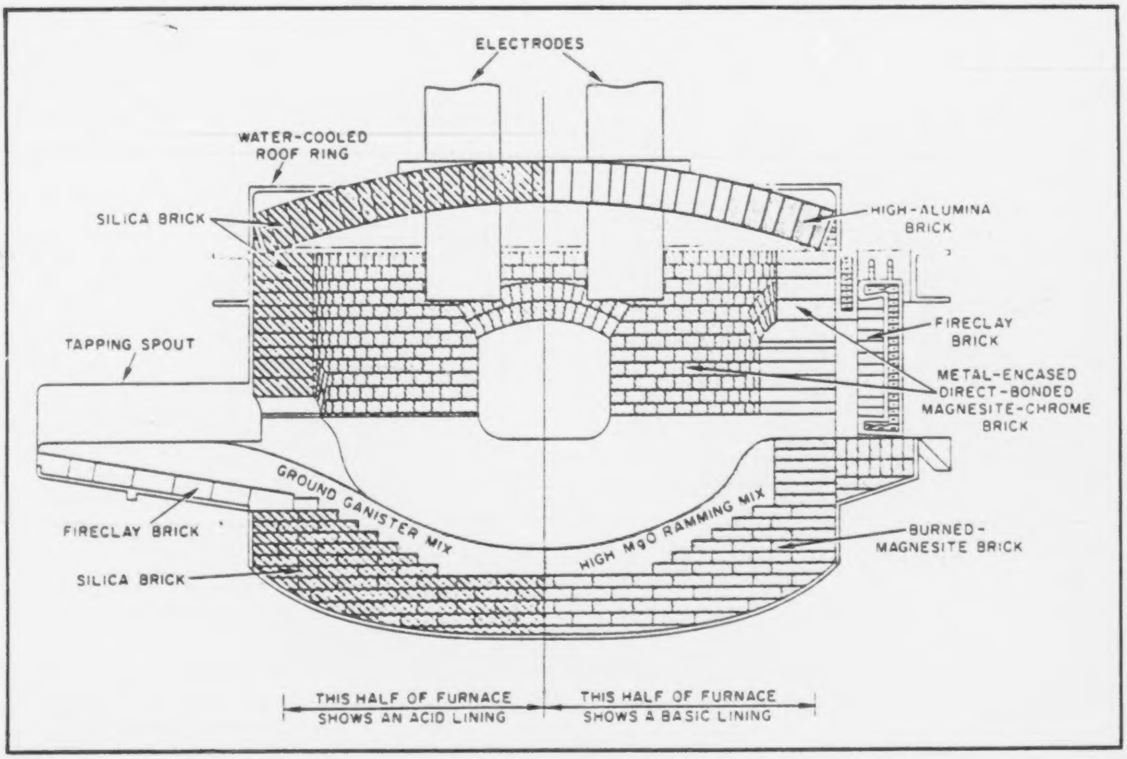
One drawback to the electric arc process is that the limited circulation of the bath under the reducing slag necessitates a long refining time. However, beginning in the late 1960s, dramatic processing changes occurred that reduced processing time and brought greater control to the production of high-quality stainless steel. These new processes have been increasingly adopted in other types of steelmaking, particularly for alloy steels and high-performance stainless steel previously made only by special vacuum-melting techniques.

THE AOD PROCESS FOR STAINLESS STEEL

One of the most significant advances made in steelmaking in this century is the Argon-Oxygen Decarburization (AOD) process for making stainless steel. The AOD process is part of a duplex process that utilizes the electric arc

Figure 2–3

SCHEMATIC CROSS-SECTION OF A HEROULT ELECTRIC-ARC FURNACE


ELECTRODES
WATER-COOLED ROOF RING
SILICA BRICK
HIGH-ALUMINA BRICK
TAPPING SPOUT
FIRECLAY BRICK
METAL-ENCASED DIRECT-BONDED MAGNESITE-CHROME BRICK
GROUND GANISTER MIX
HIGH MgO RAMMING MIX
FIRECLAY BRICK
BURNED-MAGNESITE BRICK
SILICA BRICK
THIS HALF OF FURNACE SHOWS AN ACID LINING
THIS HALF OF FURNACE SHOWS A BASIC LINING

SOURCE: *The Making, Shaping and Treating of Steel*, U.S. Steel Corporation, 1971.

furnace to accomplish the initial melting. The molten metal is close to final chromium and nickel specifications when it is then charged into the AOD vessel for decarburization (lowering the carbon level) and further refining. Figure 2-4 illustrates a typical AOD vessel operation. Currently, the AOD is the dominant process for making stainless steel in the United States and in most other noncommunist countries. An estimated 2.2 million tons of AOD capacity devoted mainly to stainless steelmaking exists currently in the United States and probably accounts for over 95 percent of stainless capacity. Further details on the AOD process and its effect on chromium are described below.

Low-carbon ferrochrome is charged by a ladle addition in normal alloy steelmaking; that is, after melting and refining, the molten steel is tapped from the furnace into a ladle where final alloying is performed. Hence, the particular furnace process in use -- oxygen, open-hearth, or electric -- will have no significant influence on chromium recovery from alloy additions. This is not true for stainless steel; to understand why, it is necessary to compare the electric furnace double-slag practice, used exclusively in the 1960s, with the processes that have almost completely supplanted it -- the Argon-Oxygen Decarburization (AOD) process and, to a lesser extent, the Vacuum-Oxygen Decarburization (VOD) process.

Yields of chromium in stainless steelmaking are higher in the United States, the EEC, and Japan than in other noncommunist countries because decarburization techniques such as the AOD process are used almost universally in producing stainless in the United States, the EEC and Japan.

In the AOD process, after the molten metal is poured from the electric furnace into the AOD vessel (as shown in Figure 2-4), an argon-oxygen mixture is injected below the surface of the metal through tuyeres near the bottom of the vessel. This causes intimate contact of the oxygen and carbon. Argon gas reduces the partial pressure of carbon monoxide above the melt and allows the carbon-oxygen reaction to proceed until very low levels of carbon and oxygen are reached. The ratio of argon to oxygen is increased as decarburization occurs. However, as the temperature of the melt increases due to the exothermic carbon oxidation reaction, chromium in the steel is also oxidized and considerable amounts could be lost to the slag.

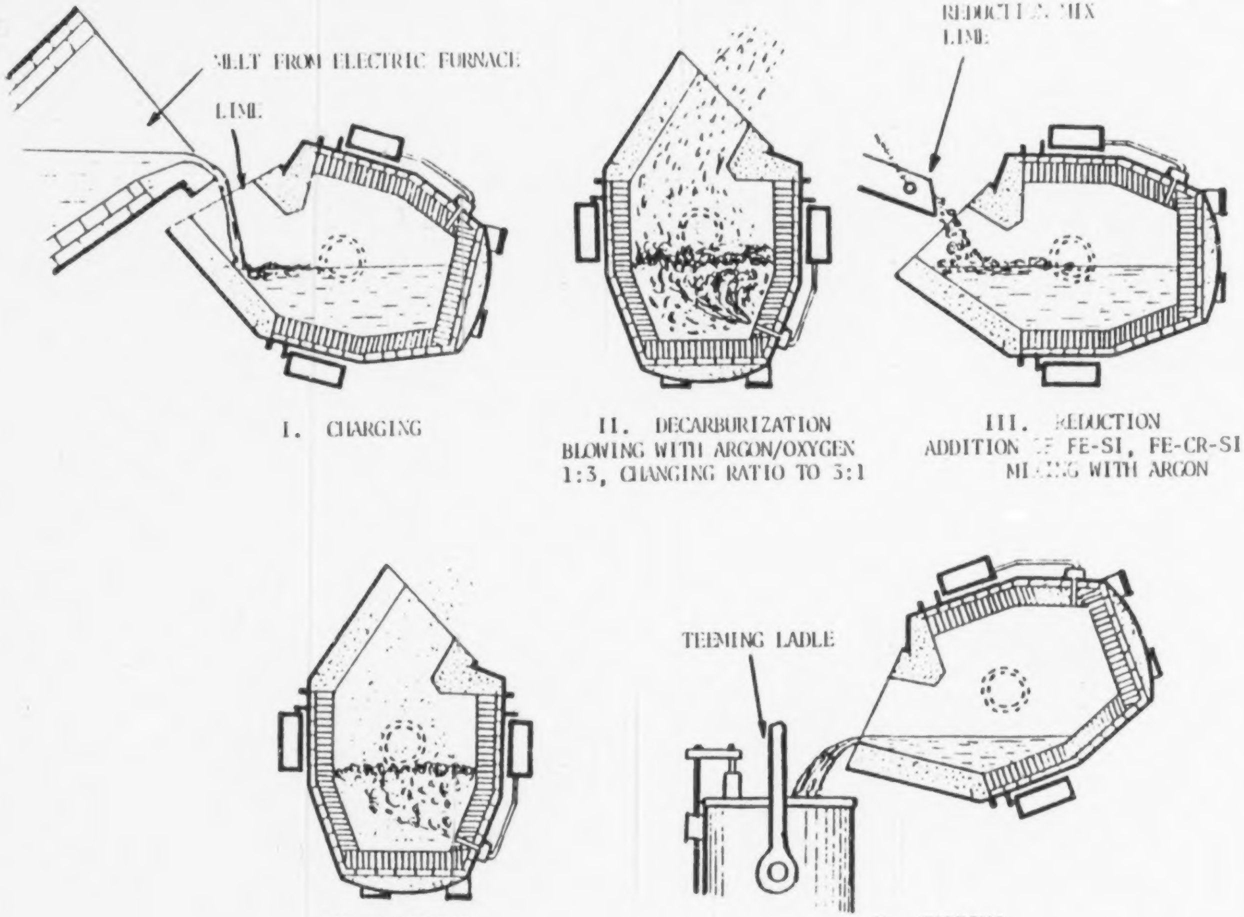
Steelmaking slags can dissolve only about 6 percent chromium oxide (Cr_2O_3), so they are saturated with Cr_2O_3 after only a small amount of chromium has been oxidized from the steel. Further chromium oxidation would then produce Cr_2O_3 as a separate phase. Therefore, the governing chemical reaction that determines the chromium content of the steel during oxidation of carbon may be written as:

$$Cr_2O_3(s) + 3\underline{C} = 2\underline{Cr} + 3CO(g)$$

where the underline denotes elements dissolved in the steel, and (s) and (g) indicate solid and gas, respectively. This reaction is very temperature-dependent (proceeding more to the right at higher temperatures).

Figure 2–4

SEQUENCE OF ARGON-OXYGEN VESSEL OPERATION FOR STAINLESS STEEL


MELT FROM ELECTRIC FURNACE
LIME
REDUCTION MIX
LIME
TEEMING LADLE

I. CHARGING

II. DECARBURIZATION
BLOWING WITH ARGON/OXYGEN
1:3, CHANGING RATIO TO 3:1

III. REDUCTION
ADDITION OF FE-SI, FE-CR-SI + LIME
MIXING WITH ARGON

IV. REFINING
BLOWING WITH ARGON ONLY
DESULFURIZATION

V. TAPPING

SOURCE: *Superalloys – Processing, Second International Conference.* 1972. Seven Springs, PA: American Society for Metals.

As the chemical equation shows, the way to minimize the amount of chromium oxidized while reaching the required low carbon content is to reduce the CO pressure, which forces the reaction to the right. The AOD process accomplishes this by dilution, with argon or nitrogen, of the oxygen blown in to oxidize the carbon, so that the CO produced is also diluted. Slag-metal reactions, such as the reduction of chromium oxide and desulfurization, are enhanced by stirring with pure argon after the desired carbon level has been reached. Argon injection also promotes the removal of dissolved gases. The VOD process achieves the same result by reduction of the overall pressure. Both methods are sufficiently effective that much higher melt-down chromium (and carbon) contents can be tolerated without excessive subsequent chromium oxidation. In addition, the higher initial chromium content, close to specification, combined with minimal chromium oxidation, requires that only nominal amounts of low-carbon ferrochromium be added after oxidation.

The older electric furnace double-slag process performs all processing steps in the same furnace. As much carbon is removed by oxidation at the highest possible temperature. This results in a significant chromium loss through oxidation as well. This is replaced by additions of ferrochrome- silicon to reduce chromium out of the slag and expensive low-carbon ferrochrome additions to bring the steel up to required chromium specifications. However, by refining the steel outside the electric furnace, the AOD and VOD processes reduce residence time in the furnace significantly, thereby raising effective production capacity. These advantages, among others, propelled the AOD process to become the predominant stainless process in the relatively short time span of eight years.

For the purposes of this study, we note four important features of the AOD process:

- Increased chromium yield (95 percent versus 90 percent for electric furnace practice);
- Flexibility in the amount of high-carbon ferrochromium added with scrap before melt-down;
- Reduction in the amount of ferrochrome-silicon and low-carbon ferrochrome that must be used; and
- Substantial reductions in alloying elements may be possible while achieving desired properties, e.g., titanium and columbium additions for carbon stabilization may no longer be needed in future AOD heats.

There has been a drastic decline in low-carbon ferrochrome usage as a result of the rapid penetration of AOD refining in the worldwide stainless steel industry. From almost two units of low carbon for each unit of high carbon in 1973, the industry moved to more than six units of high carbon for each unit of low carbon in 1981. The 6-to-1 noncommunist world average is still lower than the 13-to-1 ratio existing in Japan, which indicates that there is still more room for growth of high-carbon ferrochrome consumption in the noncommunist world at the expense of low-carbon ferrochrome consumption. AOD capacity at present dominates stainless melting capacity in the United States, while Japan and Western Europe employ a mixture of AOD and VOD. Only in the other noncommunist countries is there still appreciable use of the older electric furnace, double-slag process.

Specific alloy properties have been improved by processing them by AOD. For example, in steel castings the following improvements have been observed.

1. Enhanced homogeneity and integrity, particularly in heavy sections up to 20 inches for all grades. Less shrinkage and gas porosity problems.
2. Less hot tearing and improvement of the quality of the remaining "rehealed" tears.
3. Improvement in the Charpy V-notch transition temperature for all the low alloyed and martensitic stainless steel grades. (This means greater ductility and resistance to brittle fracture.)
4. Improved corrosion fatigue.
5. Precise control of undesired delta ferrite in austenitic stainless grades.

The AOD process is also being used for producing other types of steel products. Alloy chemistry is easy to control, allowing a greater range of scrap mix in a given heat. With the AOD process, carbon content can be held to limits low enough to permit weldability improvements, to about 0.02 percent. An average carbon level is 0.05 percent across all alloys. Not all alloys require 0.02C on the basis of their required properties. The AOD has also been found to be effective in reducing the levels of sulfur, oxygen, hydrogen, and nitrogen, thereby increasing the toughness of AOD-refined materials. The materials now being produced with the AOD process include many superalloys, tool steels, silicon steels, full-alloy steels (cast and wrought), and low-alloy steels (cast and wrought), as well as some carbon steels (cast and wrought). The degassing and desulfurization capabilities of the AOD process enable it to compete with all forms of ladle metallurgy. Also, the burden of refining is essentially removed from the arc furnace, thereby increasing shop productivity.

AOD refining is playing a vital role in the development and commercialization of the newer families of stainless steels -- the duplex grades, the nitrogen-strengthened grades (such as Nitronic 50 and 18Cr-18Mn), the precipitation-hardened grades (such as A-286), and the low-carbon interstitial ferritic stainlesses (such as 18Cr-1Mo, 18Cr-2Mo, and 29Cr-4Mo-2Ni).

The AOD process has made it possible to produce previously expensive high-performance stainless alloys such as AL-6X (21Cr-24Ni-6.3Mo) much more cheaply. AL-6X was expensive because it had to be Vacuum-Induction-Melted

(VIM) to achieve desired low impurity levels. The VIM method is about three times more expensive than the AOD method. AOD refining has improved the hot workability and ductility of these alloys by producing a much cleaner microstructure, providing better desulfurization, and reducing oxygen and nitrogen levels.

Continuous improvements are also being made to lower the cost of AOD refining itself. The trend toward more widespread AOD refining means that the costs of producing the more complex and highly-alloyed materials will decline, thereby increasing their markets. The use of chromium will be expected to increase as a result of this expansion in markets for the alloys.

The AOD is expanding its use in the following areas, among others: Jessop Steel's JS700 (similar to AL-6X with lower Mo) and Sandvik's Sanicro 28 alloy (27Cr-31Ni-3.5Mo-1Cu-0.02C) for oil country tubular goods; low-alloy steels for the same application by Standard Steel; 9Cr-1Mo, 4100, 4300, 3310, 9310 steels, Cr-Mo-V alloys, and 9Ni-4Co alloy at Republic Steel; HY-80 heavy section steels in the foundry, which have dropped cleaning and weld costs by 24 percent; and CN7M, CY40, CZ100 and Inconel 625 for heavy sections. The AOD has also enabled foundries to expand into new markets and into new types of castings, e.g. the replacement of weldments with castings.

POSSIBILITIES FOR CHROMIUM CONSERVATION AND SUBSTITUTION IN THE AOD

Some of the specific areas where consumption in steel production may be reduced are discussed below. The growth of the AOD and VOD processes in stainless steel production has had a major impact on chromium consumption, because over 50 percent of all chromium used goes into stainless steel.

The AOD and VOD processes enable attainment of overall chromium yields of 95 percent. It is unlikely that attempts to improve on this figure would be cost-effective in the absence of very large price increases for chromite. Yields can in theory be improved to 98 percent, with the loss to the slag being determined simply by the equilibrium distribution after reduction of chromium between the metal, containing 18 percent chromium and 0.5 percent silicon, and the slag.

Savings would also accrue from the final phasing out of the electric furnace, double-slag practice in favor of AOD (or possibly VOD) over the next five to ten years. Such replacement will occur in any event and would be accelerated only marginally by increases in chrome prices. Given the present AOD (or VOD) capacity in the United States, EEC, and Japan, this would mean a 5 percentage point increase in chromium yield for about 3 percent of present stainless production.

Further chromium savings seem possible for stainless steels because the AOD process permits lower carbon contents; 0.02 percent is readily attainable, compared with the current 0.05 percent. Lower carbon content would enable the chromium content to be reduced by about 0.5 percentage points. A consistently lower aim could lower the chromium content by an additional 0.2 percentage points, so the chromium content of Type 304 stainless could be lowered by about 0.7 percentage points from its current 18 to 20 percent.

The full-alloy steels containing chromium account for more than one-third of total alloy steel production and fall into three main groups: the SAE 4000 series, with approximately 1 percent chromium; the SAE 5000 series, with approximately 1 percent chromium; and the SAE 8000 series, with about 0.5 percent chromium. The specified contents are actually ranges, such as 0.4 to 0.7 percent. A lower aim for chromium can be compensated for by a higher aim for carbon or manganese. More careful alloy addition techniques, including control of atmospheric oxidation, might allow a consistently lower aim within the range, reducing the average content by 0.1 percentage points. This could save about 10 percent of the total chromium added to alloy steels in the United States. Such measures are also expected to improve chromium yields by about 3 percent, for a total savings of 13 percent.

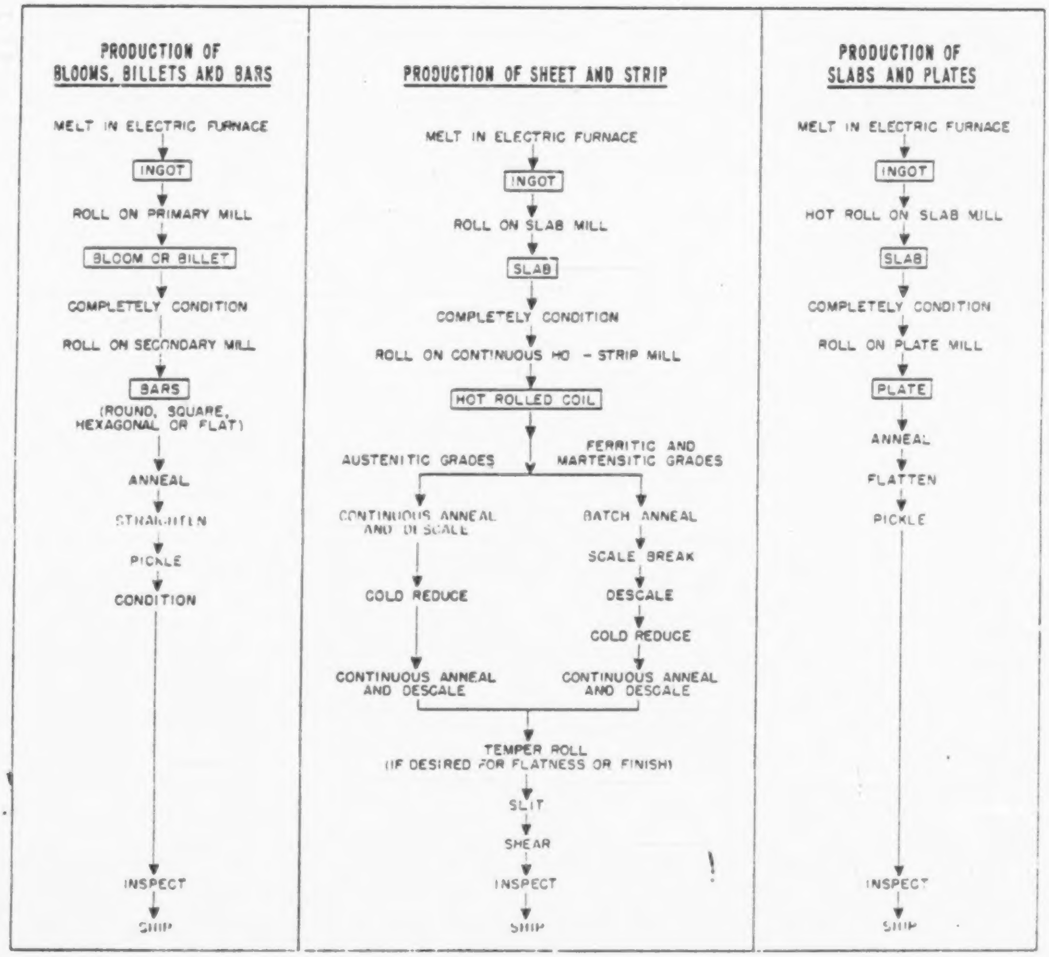
Savings of chromium in superalloys using the AOD are expected to be minimal, if any, since vacuum melting has great control and minimizes losses well at present. The reasons for moving into AOD refining for superalloys have already been cited earlier. In any of these processes, once the molten steel is refined it is usually tapped or poured from the furnace into ingot molds to solidify. The solidified, but still very hot, ingot is then sent to the primary mill. The primary mill is the first stage in forming useful products by hot rolling the ingots into blooms and slabs. In hot rolling, the ingot is passed between rollers so that the ingot cross-section is reduced to a square (as for a bloom), an oblong (as for a slab), a round, or other simple shape. The length of the ingot is increased, corresponding to the decrease in cross-section. In the concluding operations, a short length (called a crop) is cut from each end of the rolled piece as scrap, and the remaining long piece, if necessary, is cut into multiples to suit the required lengths and weights for subsequent operations. These pieces are then conditioned by removing surface imperfections, straightening bent pieces, and removing portions likely to contain serious internal defects such as voids. These blooms or slabs are still hot when they are sent from the primary mill to the secondary mills, where further rolling and working is performed on them to produce semi-finished products, such as billets (longer with smaller and more exact cross-sectional dimensions) and coiled strip, or finished products, such as rails or structural shapes (usually through forging).

Figure 2-5 indicates the sequence of steps involved in making various types of stainless steel products, from bars to sheet, strip slabs, and plates. Between the rolling steps, additional furnace reheating may be necessary to bring the workpiece up to a temperature at which it can be effectively worked by rolling.

In the figure, the annealing operation is a furnace reheating intended to soften the steel for straightening and stress-relieving. The pickling operation is designed to remove surface scale and imperfections, and is an immersion either in a sulfuric acid solution or in a molten salt bath.

Figure 2–5

FLOW SHEETS INDICATING GENERAL PRINCIPAL STEPS IN THE PRODUCTION OF STAINLESS STEEL PRODUCTS


PRODUCTION OF BLOOMS, BILLETS AND BARS
MELT IN ELECTRIC FURNACE
INGOT
ROLL ON PRIMARY MILL
BLOOM OR BILLET
COMPLETELY CONDITION
ROLL ON SECONDARY MILL
BARS
(ROUND, SQUARE, HEXAGONAL OR FLAT)
ANNEAL
STRAIGHTEN
PICKLE
CONDITION
INSPECT
SHIP
PRODUCTION OF SHEET AND STRIP
MELT IN ELECTRIC FURNACE
INGOT
ROLL ON SLAB MILL
SLAB
COMPLETELY CONDITION
ROLL ON CONTINUOUS HOT - STRIP MILL
HOT ROLLED COIL
AUSTENITIC GRADES
FERRITIC AND MARTENSITIC GRADES
CONTINUOUS ANNEAL AND DESCALE
BATCH ANNEAL
SCALE BREAK
DESCALE
COLD REDUCE
COLD REDUCE
CONTINUOUS ANNEAL AND DESCALE
CONTINUOUS ANNEAL AND DESCALE
TEMPER ROLL
(IF DESIRED FOR FLATNESS OR FINISH)
SLIT
SHEAR
INSPECT
SHIP
PRODUCTION OF SLABS AND PLATES
MELT IN ELECTRIC FURNACE
INGOT
HOT ROLL ON SLAB MILL
SLAB
COMPLETELY CONDITION
ROLL ON PLATE MILL
PLATE
ANNEAL
FLATTEN
PICKLE
INSPECT
SHIP

SOURCE: *The Making, Shaping and Treating of Steel*, U.S. Steel Corporation, 1971.

CONTINUOUS CASTING

In recent times, the traditional ingot casting procedure has been increasingly displaced by the newer continuous or strand casting technique. It is a process in which the steel is cast continuously into useful shapes, bypassing the ingot mold process. Figure 2-6 indicates the process schematically, and Figure 2-7 depicts the set-up in U.S. Steel Corporation's Gary works. The mass of solid steel casting is supported as it descends by driven pinch rolls that also control the withdrawal rate and line speed of the casting. The molds are usually water-cooled copper. Continued replacement of ingot casting by continuous casting, with attendant increases in the yield* of finished steel of 8 to 10 percent, will also result in chromium savings, simply because less raw steel input is needed for a given level of finished steel production.

Use of continuous casting worldwide is estimated to have saved some 50,000 metric tons of stainless steel in 1981. About 40 percent of all stainless in the United States is continuously cast, but only 21 percent of all steel in the United States is continuously cast at present (with an increase to 30 percent predicted by 1990). Separate figures for the percentages of stainless, carbon, and alloy steels continuously cast in other parts of the world are not available, but continuous casting in 1981 did account for 45 percent of total steel production in the EEC, 71 percent in Japan, and an average of 36 percent in the other noncommunist countries. The entire noncommunist world in 1981 produced 44 percent of its steel by continuous casting.

ADVANCED MELTING TECHNOLOGY

High-performance alloys such as nickel-base and cobalt-base superalloys and, increasingly, the specialty iron base-alloys, some stainlesses, and tool steels are produced using advanced melting techniques. These techniques involve melting under a vacuum in order to impart the necessary cleanliness, chemistry control, structure, and properties to the alloys.

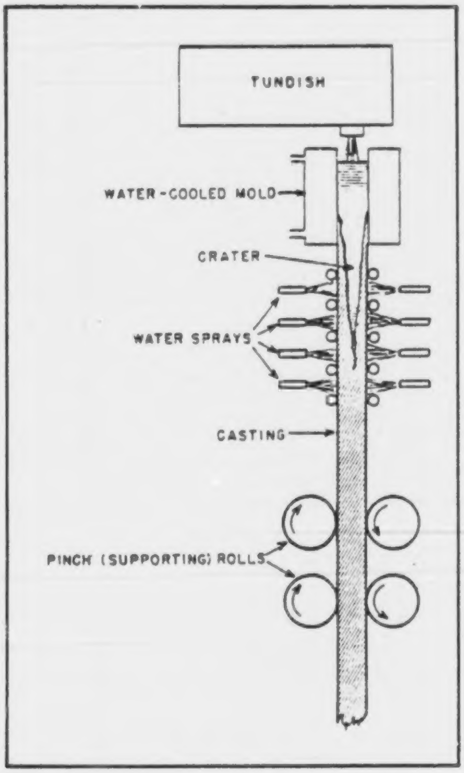
The need for low pressures in the production furnace resulted when reactive alloying elements such as aluminum, titanium, and columbium began to be added to high-performance superalloys for imparting the high-temperature strength, ductility, and fatigue properties necessary for jet engine service. Other constituents, such as chromium, molybdenum, tungsten, and tantalum, also have varying affinities for oxygen and nitrogen, so vacuum-melting became a

---

*This yield savings only involves savings in input material and does not include scrap recovery. Essentially, less scrap is generated by the continuous casting process and this would be handled as is scrap from the ingot casting route.

Figure 2–6

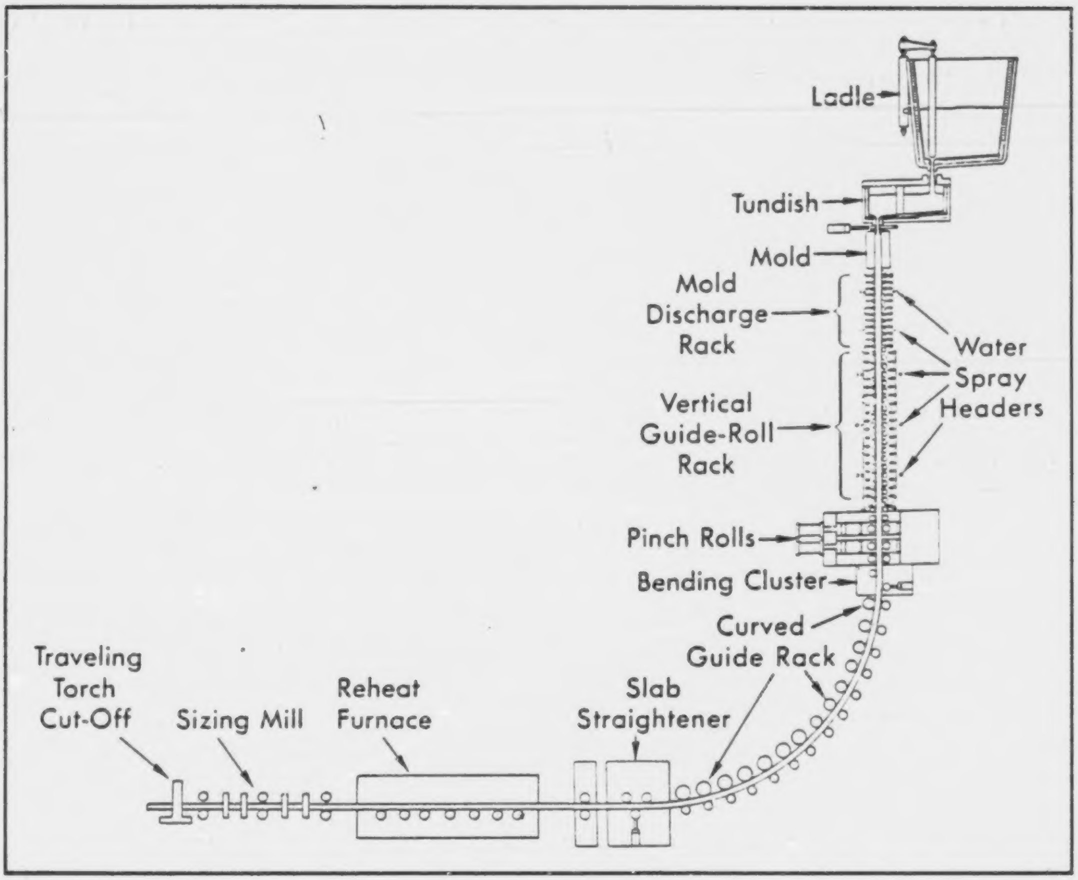
SCHEMATIC DIAGRAM DEPICTING HOW LIQUID METAL PERSISTS IN THE CENTER OF A CONTINUOUS CASTING FOR A CONSIDERABLE DISTANCE AFTER THE CASTING LEAVES THE WATER-COOLED MOLD, FORMING A SO-CALLED "CRATER"


TUNDISH
WATER-COOLED MOLD
CRATER
WATER SPRAYS
CASTING
PINCH (SUPPORTING) ROLLS

SOURCE: *The Making, Shaping and Treating of Steel*, U.S. Steel Corporation, 1971.

Figure 2–7

SCHEMATIC VERTICAL CROSS-SECTION OF THE GARY WORKS SLAB CASTER, SHOWING THE RELATIVE LOCATIONS OF THE SUCCESSIVE OPERATING UNITS


Ladle
Tundish
Mold
Mold Discharge Rack
Water Spray Headers
Vertical Guide-Roll Rack
Pinch Rolls
Bending Cluster
Curved Guide Rack
Traveling Torch Cut-Off
Sizing Mill
Reheat Furnace
Slab Straightener

SOURCE: *The Making, Shaping and Treating of Steel,* U.S. Steel Corporation. 1971.

prerequisite in reducing these two elements to the lowest level possible, because they tend to form inclusions and other unwanted precipitates, and to cause defects that undermine performance.

Vacuum-melting also allows removal of other unwanted trace elements such as lead, bismuth, tellurium, selenium, and thallium, which can, among other things, cause severe embrittlement. They are removed by degassing out of the melt.

The primary melting technique used today is Vacuum-Induction-Melting (VIM), developed along with high-strength superalloys in the early 1950s. A charge of solid scrap, alloys, ferroalloys, and other materials is melted under vacuum conditions in a refractory-lined crucible by heat generated from electric currents induced in the charge. Impurities are removed as gases and there is no contamination from air or slag. The metal is cast under vacuum into ingots for processing into mill products or into electrodes for remelting to obtain further refinement and improvement in ingot structure. Usually the VIM product is further treated by a number of remelting and refining techniques, which depend on the alloy and the application involved (see Figure 2-8). Smaller VIM ingots may be remelted and investment-cast into jet engine turbine vanes or blades by new techniques such as directional solidification or single-crystal casting. VIM furnace capacity in the United States has been estimated as between 80 and 90 million pounds.*

For hot-working the alloys for larger-size turbine engine parts, a secondary melting and refining step is required. The VIM product cannot be worked directly because of compositional micro- and macrosegregation, nonuniform grain size, and shrinkage. These problems have been overcome since the early 1960s by vacuum arc remelting, or VAR. The VIM ingot becomes an electrode in VAR, positioned vertically and remelted by the electric arc into a water-cooled crucible. Metal is transferred drop by drop until the ingot is slowly built up. This results in a uniform and refined grain structure, and compositional segregation is removed. Some impurities are also removed as gases.

Another refining process in use is Electroslag Remelting, or ESR, in which either electric furnace electrodes or VIM electrodes are progressively remelted and solidified in a water-cooled copper mold under a blanket of molten flux. The process is performed in air, not under vacuum. Melting is due to heat generated by the resistance of the molten flux to electric current that passes between the electrode and the solidifying ingot. Refining occurs as molten metal passes through the flux, and impurities react with the flux, either to form a removable slag or they vaporize off. The progressively solidified ingot is homogeneous and free of shrinkage defects.

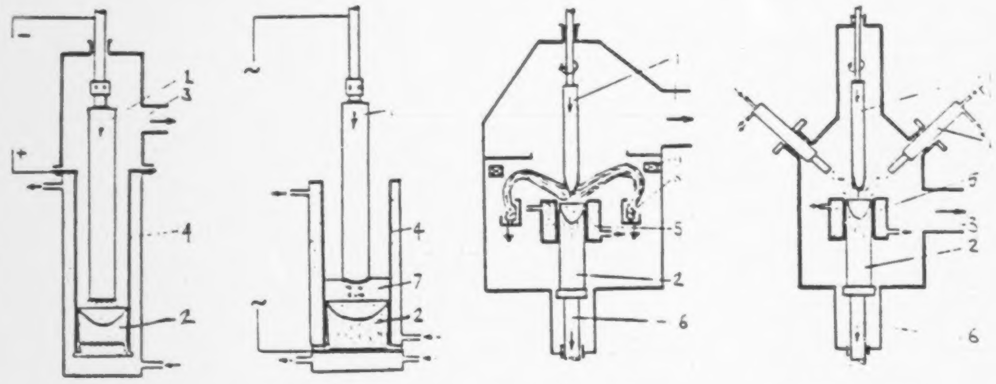
The ESR process offers easier control of the melt than VAR because the flux bath provides uniform heat distribution and reduces thermal gradients, but compositional control needs close attention as a result of the oxidizing

---

*American Metal Market, Vacuum Metallurgy Supplement, June 4, 1982, p.3A.

Figure 2–8

PRINCIPAL CONSUMABLE ELECTRODE REMELTING SYSTEMS



Vacuum Arc Furnace   Electroslag Furnace   Electron Beam Furnace   Plasma Arc Furnace

1. Electrode
2. Ingot
3. Vacuum Port
4. Crucible
5. Mold
6. Withdrawal System
7. Flux Pool
8. Electron Guns
9. Magnetic Deflectors
10. Plasma Guns
11. Argon

SOURCE: *Superalloys – Processing, Second International Conference.* 1972. Seven Springs, PA: American Society for Metals.

tendency of the flux bath. ESR offers good nitrogen retention for the nitrogen-alloyed superalloys and steels. In the U.S.S.R., ESR was developed to high technological standards in the early 1960s and has subsequently found very wide application.

Electron Beam Refining (EBR) utilizes the energy of a highly-accelerated electron beam to produce heat generated in the material itself for melting and refining under high vacuum. EBR has been used in the United States mostly in melting refractory alloys of tantalum and columbium. The process uses either VIM ingots or scrap, powder, or pellets. The melted metal drips into a water-cooled mold, forming a pool and, subsequently, an ingot, which is slowly withdrawn (i.e., continuously cast) to keep the level of the pool constant. The refining of impurities is very efficient because of the intense, localized heating of the electron beam. EBR has excellent flexibility with respect to type of feedstock and is being used increasingly for scrap recycling. EBR could be added as an intermediate processing step between VIM and VAR. The final step would need to be VAR since it is the only solidification process that has been certified for producing jet engine parts. The certification problem may partially explain why it has not spread very rapidly to superalloys and other areas. However, some view EBR as having great potential in recycling superalloy scrap for returning it to a purity acceptable for aerospace use. In foreign countries, EBR has enjoyed more activity in Germany and the U.S.S.R. than in the United States, particularly in bearing steels.

Another technique akin to EBR is plasma arc remelting, which remelts the VIM-cast ingot by bombardment with a high-energy gas plasma and is an alternative to VAR. The technique is not widely used in the United States, but is being used to a significant extent in Japan and the U.S.S.R. Like EBR, it has potential for remelting and purifying superalloy scrap and returning it for aerospace use. Again, its use has been limited due to its lack of certification for jet engine parts.

Another reason for the lack of interest in EBR and plasma arc remelting may be the perception that some combination of processes involving the AOD is superior. One such combination cited was electric furnace melting followed by AOD refining and electroslag remelting for reprocessing superalloy scrap. The AOD process has been more prevalent in the United States than in other parts of the world.

Most of the technical advances made in melting technology have been accomplished with the very-high-performance and difficult-to-process superalloys. Open melting in electric arc and induction furnaces in combination with auxiliary refining by vacuum processes or AOD is acceptable only for materials with lower to medium-high temperature properties. The vacuum melting and remelting methods are especially suitable when there are substantial amounts of reactive elements present in alloys requiring very tight composition control, e.g. in alloys containing hafnium or titanium.

However, AOD and ESR are generally preferred for alloys without reactive elements that contain volatile alloying elements. These are expected to be the predominant technologies for at least the remainder of this decade.

The push that is evident in the industry toward cleaner metal for higher-performance alloys will make the newer technologies increasingly important and pervasive, although they are already important commercially. The newer technologies will continue to be used for superalloys and will be used increasingly for different types of specialty steels and stainless steels. Full automation of advanced melting techniques for "master alloys" appears to be some time off in the future. Limited use of robots exists for producing molds, but more sophisticated vacuum pressure sensors, temperature sensors and optical sensors for slag are needed. Also, the nature of the heats usually varies so much that process controls done automatically would be very complex. Adequate software has not been developed to do this yet. To date, there do exist so-called VIM fast cycle units which automatically produce the superalloy turbine blades and vanes (to be described later). But here the heats do not vary in composition as the master alloy heats do. The main advantage cited for automation in this area is quality control, which increases consistency of product and yields.

FORGING TECHNOLOGY

When a component of a machine takes shape on the drawing board of a design engineer, the method to be used in its manufacture may still be entirely undetermined. The number of possible manufacturing processes is increasing steadily and the optimum process can be found only by the careful weighing of technological advantages and limitations in relation to the economy of production.

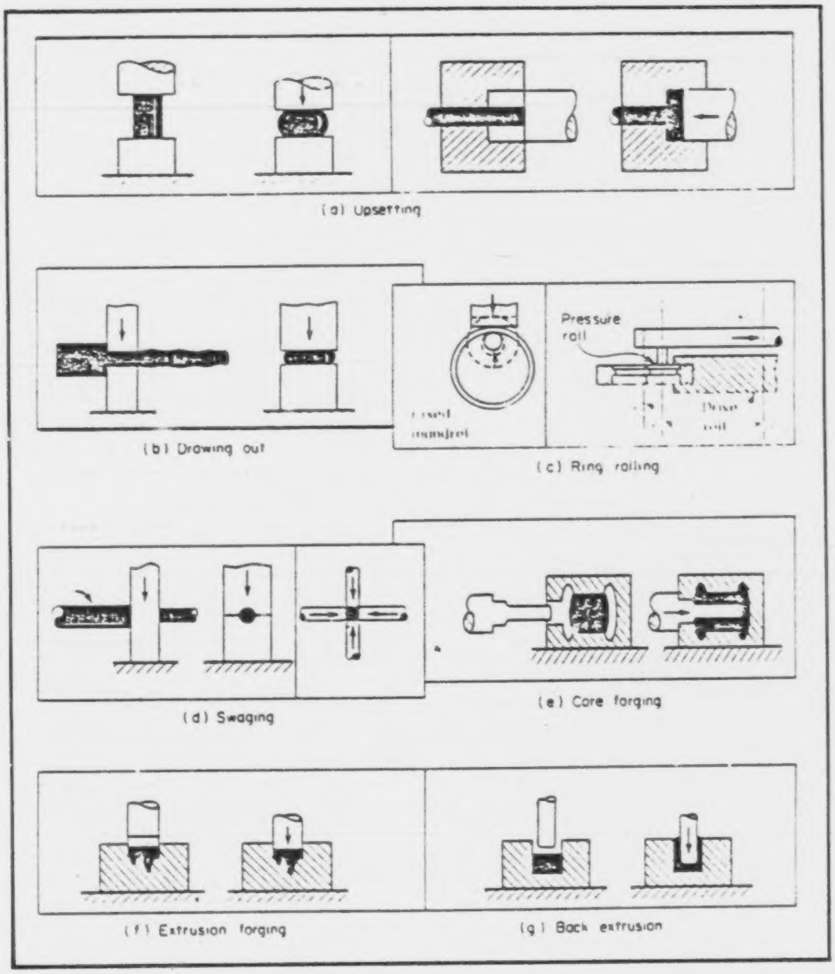
Forging is an operation of metal shaping by elevated temperature plastic deformation achieved by the action of hammers or presses and the use of different types of dies. Forging spans a wide range of equipment and techniques, and has much to offer in terms of quality. Forging yields materials of high density and fine grain with no internal cavities. It has the unique advantage of producing a continuous-grain flow pattern; that is, the metal grain structure has alignment in a uniform direction along the workpiece (usually called texture), which results in enhanced strength, ductility, and impact and fatigue resistance.

Several of the major methods of forging are described below and are illustrated in Figures 2-9 and 2-10.

- Upsetting -- compression in the longitudinal axis of the work.
- Drawing out -- stretch-out of the work by a series of upsets along the length of the workpiece.

Figure 2–9

PRINCIPLES OF SEVERAL TYPES OF FORGING OPERATIONS


Pressure roll
Fixed mandrel
Drive roll

(a) Upsetting

(b) Drawing out

(c) Ring rolling

(d) Swaging

(e) Core forging

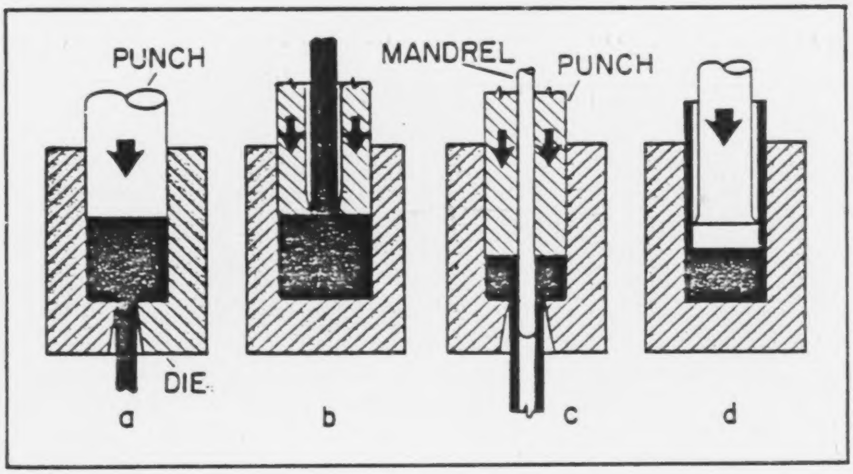
(f) Extrusion forging

(g) Back extrusion

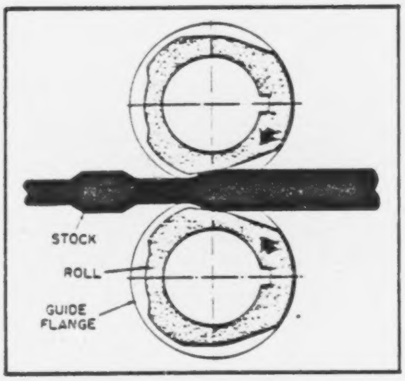
SOURCE: *Stainless Steel Handbook.* ASM.

Figure 2–10

FORWARD EXTRUSION, (A); BACKWARD EXTRUSION, (B); TUBE EXTRUSION, (C); AND CONTAINER EXTRUSION, (D)


PUNCH
MANDREL
PUNCH
DIE
a
b
c
d

ROLL FORGING


STOCK
ROLL
GUIDE FLANGE

SOURCE: *Forging Topics.* Vol. 36, No. 4. 1978.

- Impression-die forging -- two dies are brought together and the workpiece undergoes plastic deformation until its enlarged sides touch the side walls of the die. A small amount of material begins to flow outside the die impression, forming a flash that is gradually thinned. Die forging accounts for the vast majority of commercial forging production. Closed die forging, a special form of impression-die forging, does not depend on the formation of flash to achieve complete filling of the die. Since pressing is often completed in one stroke, careful control of workpiece volume is necessary to achieve complete filling without generating extreme pressures in the dies from overfilling.

- Extrusion -- the workpiece is placed in a container and compressed by ram movement until pressure inside the metal reaches flow-stress levels. The workpiece completely fills the container and additional pressure causes it to leave through an orifice and form the extruded product.

- Extrusion forging -- similar to normal extrusion but the metal is forced into a die opening by restricting flow in other directions.

- Back extrusion -- often used to make containers by employing a punch to force the metal in the die to flow opposite to the punch direction, i.e., up the sides of the die around the punch.

- Roll forging -- performed on a rolling mill. Forging tools are affixed onto the rolls that contact the workpiece and multiple passes with 90-degree rotation are performed.

- Swaging -- a circumferential compression performed to lengthen a workpiece.

- Core forging -- displacing metal with a punch to fill a die cavity.

- Ring rolling -- radial compression on a ring shape to increase diameter. As diameter increases, the thickness of the ring decreases.

- Cold forging -- may involve impression die forging or true closed die forging and is done at temperatures between room temperature and 1100°F, considerably cooler than those used for normal hot forging. Cold forging is used mainly for carbon and standard alloy steel parts that rarely exceed 25 pounds and require little finishing. The high unit forces required at the lower temperatures make tool design and manufacture extremely critical and costly. The process is used for many common and cheap parts made in large quantities.

- Precision forging -- normally means close-to-final form or near net shape forging. It is a refinement of existing techniques to the point where the part can be used with little or no subsequent machining. Improvements cover not only the forging method itself but extend to preheating, descaling, lubrication, and temperature control practices.

The decision to use precision forging depends on the relative economics of additional operations and tooling versus elimination of machining; it is a matter of obtaining the optimum part properties in a cost-effective manner. Because of higher tooling and development costs, this technique is usually limited to high-quality applications such as in the superalloy parts for jet engines. The two major precision forging processes now in commercial use are isothermal forging (or Gatorizing, a process patented by Pratt and Whitney) and hot die forging. These two techniques are the most advanced forging methods now in use:

--Isothermal forging -- differs from conventional forging in that the workpiece is heated to the same temperature as the forging die, thus preventing heat loss and surface chilling of the component. The die temperature for isothermal forging is in the 1750° to 1800°F range, compared to 700° to 800°F for conventional forging. Through reduction of the heat loss from stock to die, the plastic deformation of metal during the shaping process is significantly improved. The major benefit resulting from this is that aerospace parts can be forged close to the final end-use weight and configuration, or "near net shape." The entire isothermal forging operation is performed in a vacuum, or inert gas atmosphere, from the introduction of the metal stock (or preform) into the heating chamber, to its removal after forming. The forged part is often a "sonic shape," a part that can be ultrasonically inspected with a minimum of machining. Pratt and Whitney's Gatorizing Process is a type of isothermal forging. This method can decrease the amount of input material by 50 percent, and therefore it decreases the buy-to-fly ratio. This technology is routinely used now for the forging of some engine components such as turbine disks of highly alloyed superalloys which could not be fabricated properly by conventional techniques. The only difference between Gatorizing and conventional isothermal forging is the inclusion of operations to impart superplastic properties to the workpiece. Since most isothermal forging is done on superplastic materials, the two terms are used interchangeably.

--Near-isothermal forging -- sometimes referred to as hot die forging, differs from isothermal forging in that the die system is heated to within 150 to 300°F of the stock temperature. The forging operation is performed in an air atmosphere and can be adapted to a broad range of conventional hydraulic presses, ranging from 6,000 tons to 35,000 tons. As in the previous case, the input material is reduced, but to a lesser extent than in the case of isothermal forging.

Usually, after forging the part is given a heat treatment to restore strength and ductility.

Advanced forging operations at present use powder preforms that go into the forging die rather than wrought metal stock. Stable ultrafine grain sizes can be developed in powder-processed advanced superalloys that permit these materials to be deformed superplastically. Since the temperature is so high, the actual deformation is performed much more slowly, and in these regimes the superalloy becomes very easy to work; i.e., it becomes superplastic. Therefore, the final part needs minimum machining because of the detail possible in the forged part configuration. Figure 2-11 illustrates the typical Gatorizing forging apparatus. The induction coils provide the heating.

Isothermal forging of powder alloys has been important because it has enabled the production of superior parts for jet engines from complex nickel-base superalloys such as IN-100, RENE 95, and MERL 76, which could not be fabricated into reliable parts by any other method. The chromium and cobalt levels in these and other powder alloys may remain the same or increase over alloys previously used for the same application. The use of new forging technology does not necessarily enable reductions in critical metals content because the main factor is performance of the part, and any alloying level will be used that will increase the performance. However, the savings in input raw material to the gatorizing process will usually result in a net saving in chromium or cobalt even if their alloying contents might have increased somewhat from previous alloys in the same application.

In the forging process, the controlled deformation (usually at elevated temperatures) results in greater metallurgical soundness and improved mechanical properties of the material. In most cases, forging stock has been pre-worked to refine the dendritic structure (the structure caused by segregation of alloy components upon solidification) of the ingot and remove defects or porosity from the casting process. This produces the alignment (grain flow) in directions requiring maximum strength. Working the material between impression dies also achieves grain refinement that yields maximum strength potential and high reliability with minimum property variation from piece to piece. Properly developed grain flow in forgings closely follows the outline of the component, which is not the case with a casting. Forgings also achieve superior chemical uniformity by dispersing any massive segragation of alloys or nonmetallics that might otherwise cause unpredictable response to heat treatment or jeopardize component performance.

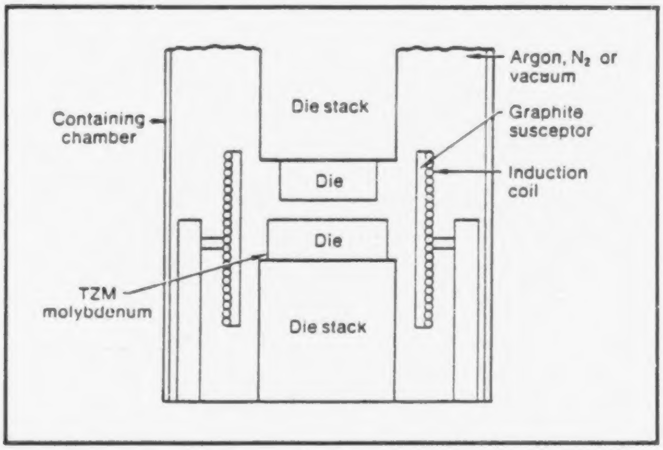
Forged products are becoming more attractive because of their excellent reliability, improved tolerance capabilities, and the higher efficiency with which forgings may be machined and further processed by automated means. Most of the newer processes such as Gatorizing are becoming fully automated.

POWDER METALLURGY TECHNIQUES

Several newer developments in processing enable the formation of parts starting with metal alloy powders. New powder metallurgy techniques such as hot isostatic pressing and cold isostatic pressing are offering great potential for making parts with superior properties. Rapid solidification technology for preparing metal powders using rapid cooling techniques

Figure 2–11

SCHEMATIC OF GATORIZING FORGING APPARATUS


Argon, N_2 or vacuum
Die stack
Containing chamber
Graphite susceptor
Die
Induction coil
Die
TZM molybdenum
Die stack

SOURCE: *Alloys for the Eighties.* **Amax Incorporated. p. 69.**

promises interesting future prospects but is not likely to become commercialized for superalloys or the various steels for some time to come. These techniques will be described below.

HOT ISOSTATIC PRESSING

In this process ("HIPing"), powder is placed in a container and then preheated inside a high-pressure chamber, as shown in Figure 2-12. The powder is thereby pressed and sintered but, unlike the case of mechanical hot pressing, pressure is uniformly distributed throughout the piece being formed. The HIPing process yields components having reproducible mechanical properties throughout the part because of the uniform dispersion of alloy components when powder metallurgy is used. Tooling is expensive; thus, cost depends greatly on the complexity of the part and the number of components in each batch. HIPing can be used to consolidate preforms for isothermal or near-isothermal forging. HIPing is now also being used to treat precision castings in order to close internal cracks and reduce or eliminate porosity. This has been highly successful in improving the performance of superalloy castings. An example is in a Type 17-4PH stainless steel impeller, which had a 90 percent reject rate due to microshrinks after machining. HIPing cut the reject rate almost to zero and saved hundreds of dollars per engine. The elimination of porosity greatly reduces the chance of premature failure and results in fewer rejects in final machining operations. At present, HIPed components are not used in systems because they are not considered sufficiently reliable.

COLD ISOSTATIC PRESSING

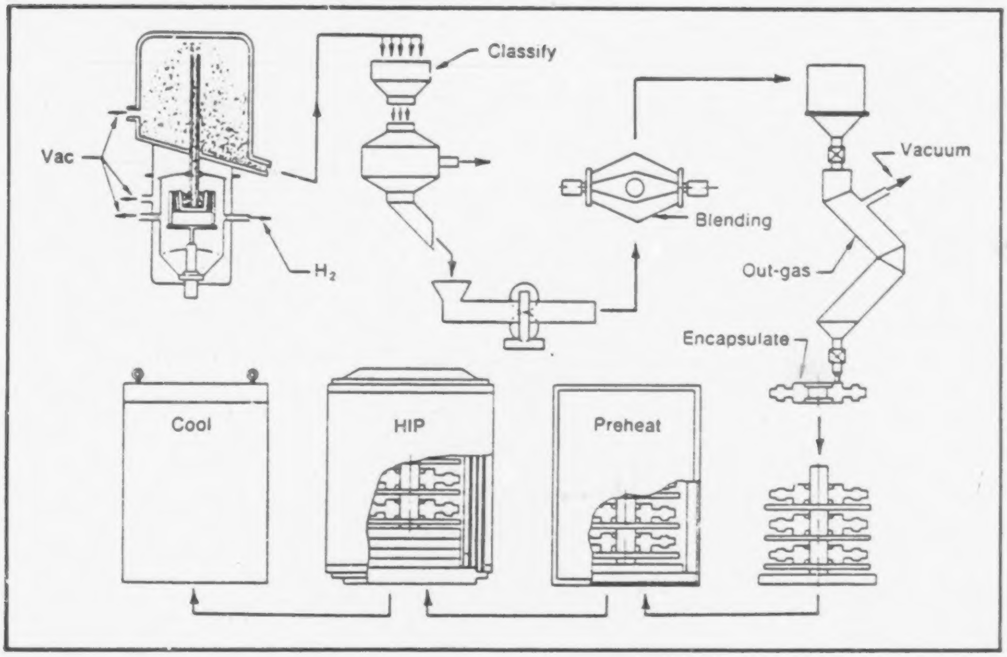
"CIPing" is similar to HIPing, but it is carried out at room temperature and followed by sintering at high temperature without pressure. The raw material is acicular powder, to which alloying elements may be added if desired. Porosity of the pressed and sintered component can be reduced by treating the sintered part in a hot isostatic chamber.

RAPID SOLIDIFICATION

In conventional casting -- the process by which a molten metal is solidified to yield an ingot -- cooling rates in the liquid state are usually less than 100°C per second. Since most alloys freeze over a range of temperature and liquid concentration, metallurgical processing at these rates leads to segregation of some elements contained in the alloy. The segregation of these elements, which is aggravated by the normal impurity levels of iron, silicon, manganese, and other common alloy-comprising metals, is the ultimate origin of most inclusions. These inclusions are the primary causes of fatigue-crack initiation and result in poor toughness and strength properties of the alloys.

Figure 2–12

FLOW DIAGRAM FOR HOT ISOSTATIC PRESSING


Classify
Vac
Vacuum
Blending
H_2
Out-gas
Encapsulate
Cool
HIP
Preheat

SOURCE: *Alloys for the Eighties.* **Amax Incorporated, p. 78.**

Recent technological developments have demonstrated the possibility of alleviating this problem by increasing the cooling rate during the solidification process. Whereas cooling rates of up to 1,000,000°C per second have been obtained in the laboratory, in commercial applications more modest rates may be adequate for improving structure, avoiding harmful inclusions, and, in certain cases, producing alloy compositions that are otherwise unobtainable.

Very rapid cooling is obtained by forming powders of the alloy through atomization, which increases the heat transfer rate enormously -- the smaller the particle size, the faster the cooling rate. Atomization can be performed by a gas (argon or nitrogen) jet or a water jet impinging on the molten metal and breaking up the liquid metal into droplets. Gas atomization is practiced commercially in various processes; water atomization yields a fully-oxidized and irregularly-shaped (rather than spherical) powder, so it has not been used.

The other processes are the rotating electrode process (REP), the soluble gas process (SGP), and the rapid solidification rate (RSR) process.

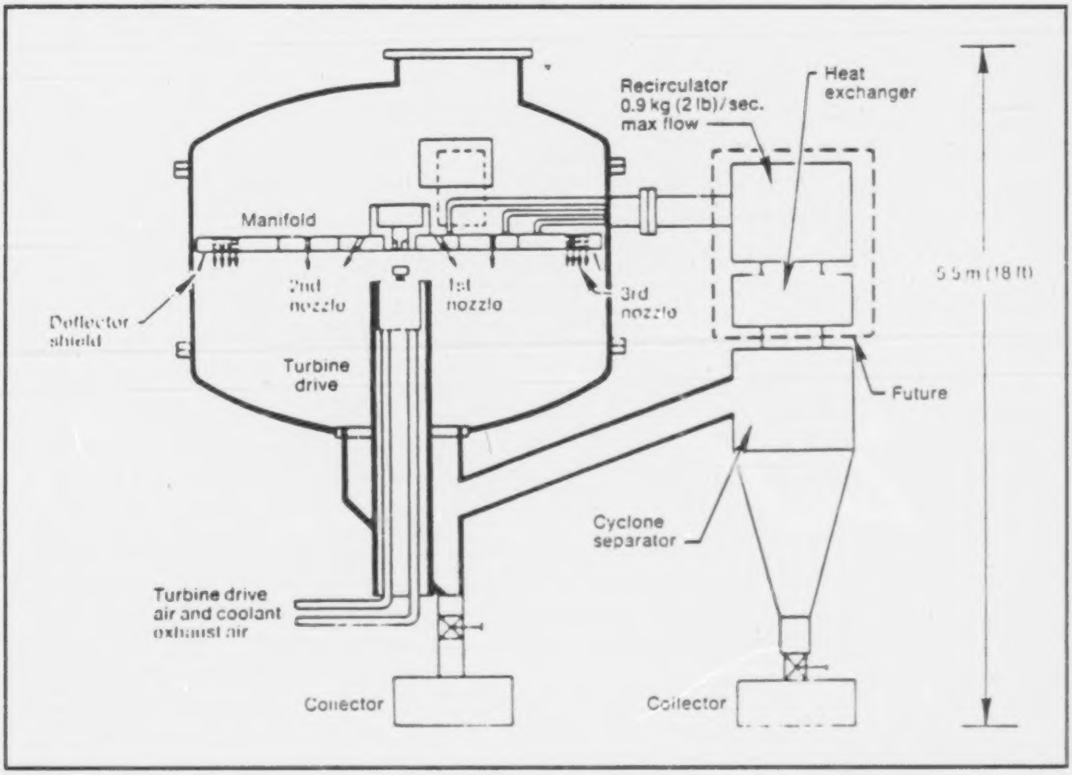
- In the rotating electrode process (REP), a consumable rotating electrode of the desired alloy is melted by an electric arc from a nonrotating tungsten electrode positioned directly opposite it. As the alloy electrode rotates, it spins off molten droplets that freeze in flight and drop to the floor of the chamber. The chamber interior is evacuated and backfilled with helium or argon prior to making the powder. The process is being commercialized and only small quantities of powder are available. A variation of the REP process is the Plasma Rotating Electrode Process (PREP), through which a higher-quality powder is produced.

- In the soluble gas process, the alloy is melted and contained within a melt chamber. During melting, the melt is superheated and the melt chamber is pressurized with hydrogen gas. The melt chamber is positioned directly below an upper expansion chamber, which is maintained at about 10 torr, or about 1/76th of an atmosphere. When the melt is ready, a valve is opened between the two chambers to allow the gas-saturated molten metal to transfer to the upper expansion chamber through a ceramic tube. When this happens, the sudden release of soluble gas that occurs as the molten alloy reaches the orifice atomizes the alloy as a fine spray that freezes and is collected at the bottom of the chamber as fine powder. Hydrogen is essentially all released from the metal in the vacuum chamber and therefore does not pose a hydrogen embrittlement problem. There are no apparent safety problems with using hydrogen in the process.

- In the newer RSR process, rotary or centrifugal atomization is used (as shown in Figure 2-13). This process was adapted with superalloy powders in mind. A VIM superalloy charge is melted in the crucible at the top of

Figure 2–13

SCHEMATIC OF CENTRIFUGAL ATOMIZER SHOWING THE ARRANGEMENT FOR HIGH MASS FLOW GAS QUENCHING – RSR PROCESS


Recirculator
0.9 kg (2 lb)/sec.
max flow
Heat
exchanger
Manifold
2nd
nozzle
1st
nozzle
3rd
nozzle
Deflector
shield
Turbine
drive
5.5 m (18 ft)
Future
Cyclone
separator
Turbine drive
air and coolant
exhaust air
Collector
Collector

SOURCE: *Alloys for the Eighties*. Amax Incorporated. p. 69.

the apparatus. The metal is then is poured into a transfer system, which directs a stable continuous flow of metal into an atomizer that has a disk spinning at 24,000 rpm. The spinning disk atomizes the molten metal into particles ranging from 10 to 100 microns. These particles are subsequently cooled in a helium gas jet. The cooling rate achieved during gas quenching is about 1,000,000°C per second. The powders so produced have a higher incipient melting point than slowly-solidified metal by 40° to 80°C. This higher temperature of melting permits higher solution temperatures of the consolidated material. This in turn permits greater homogeneity and therefore strength due to the more rapid diffusion and redistribution of elements possible at the higher temperatures. The RSR process is commercialized. Powders made from it are limited to nonrefractory and nonreactive melts. The newer rapid-cooling technologies attempt to reduce the size of the powders so as to speed up the heat transfer rate.

Industry sources indicate that it may be a long time before rapidly-solidified powders become cost-effective and practical to use in the production of superalloy parts for jet engines and gas turbines, whereas these techniques are fully commercial for other metals such as aluminum.

PRECISION CASTING

The casting of metal parts is common to all of the alloys discussed in this report. Typically, a part is cast by pouring molten metal into a hollow mold made in the shape of the part. Much research has been done to control the cooling and solidification process in order to avoid internal voids and defects as well as the macro- and microsegregation of alloying elements, which invariably occurs with cooling. In addition, the resulting grain structure can be nonuniform because cooling near the mold metal interface is more rapid than at the center of the part. Such nonuniform grain size leads to irregularities in mechanical properties of the final part. A portion of this problem can be corrected by further heat treatment of the casting and reannealing to homogenize alloying additives and to bring about a refining of grain size that will increase strength and improve ductility.

In the area of high-performance alloys for aerospace applications, newer precision casting techniques have been developed to improve the properties of the part produced, particularly strength, toughness, and in-service operating temperatures, which translate into increased life and improved fuel efficiency.

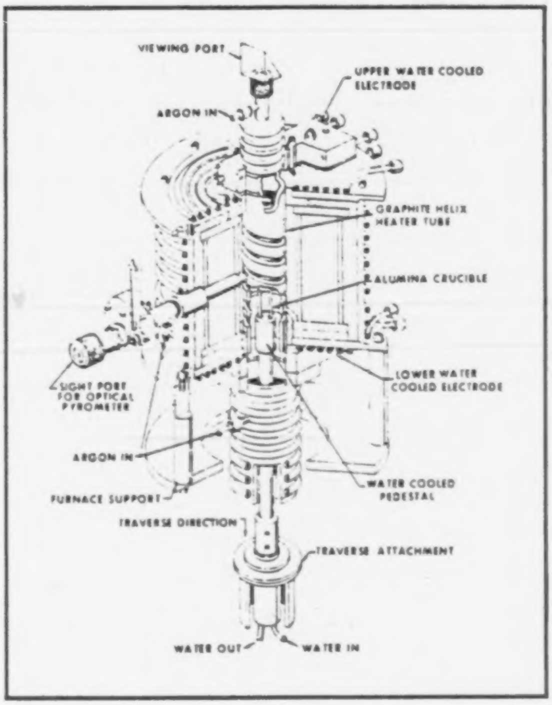
Precision casting involves variations and improvements on the conventional investment casting technology specifically designed to produce near net shape parts, minimizing further machining and reducing the quantity of input material required. The investment casting process involves the formation of a wax or polymer replica of the desired part. A ceramic mold is slip-cast around this replica, and the mold is fired in a furnace to sinter the mold and burn out the replica inside. The molten metal is then poured into the mold. In one variation (the lost wax process), the molten metal is poured directly into the mold without prior burnout of the wax replica, allowing the hot metal to vaporize the wax away.

Two variations of this kind of precision casting involve casting a columnar or directional grain structure (along the length of the post) and the casting of a single-crystal structure. These techniques are illustrated in Figures 2-14 and 2-15 and are being applied to the casting of jet engine turbine blades and vanes. The metal is cast into the investment casting mold and the heat is removed in a controlled unidirectional manner to form the solid part. The mold is attached to a water-cooled copper chill inside the confines of an induction-heated cylindrical graphite susceptor. A holding period of a few minutes allows some growth of solid to be initiated off the chill surface and a temperature profile is established in the casting. The mold is then withdrawn from within the heated zone at a specified rate. The only difference in the technique used to produce the single-crystal blade is the use of a multiple-turn constriction adjacent to the chill plate, as seen in the figure, which permits only one grain to enter the airfoil portion of the mold. The key parameters to be controlled are the thermal gradient, the liquid/solid interface, and the rate of withdrawal of the mold from the heated zone inside the susceptor. The advantages of the directionally-solidified columnar grain castings over conventional castings are: greater thermal fatigue life (8X); greater rupture life (2X); and greater rupture ductility (4X). With single-crystal castings, the advantages are even greater since there are no grain boundaries. Moreover, boundary-strengthening elements such as zirconium, carbon, boron, and hafnium are not needed. In addition, the parts can be furnace-annealed (or solutionized) to higher temperatures for more homogeneous castings because the alloy has a higher incipient melting point. Single-crystal blades are being incorporated into some of the latest models of jet engines. The technology was pioneered principally by Pratt and Whitney Aircraft and subsequently licensed to their suppliers of alloy materials and parts. The processes have now been automated using preprogrammed cycles but not to the extent that operators have been eliminated. Such automation primarily improves quality control and therefore the yield of parts.

Variations on the investment casting process have been spreading to more conventional applications more recently. In the foundry industry, the lost foam and evaporative casting techniques have been applied to making automotive parts for GM and Ford, respectively. The two processes are similar and involve forming plastic foam (styrofoam) models of the parts and coating them with refractory materials. Casting sand is formed around them and then the molten metal is poured into the molds. The plastic is evaporated leaving the metal in the void left behind. The technique is now in mass production on a larger scale than for previously used techniques which used the same equipment such as full-mold casting. The processes are expected to be fully automated eventually. The processes currently are being used to make parts from aluminum alloys.

Figure 2–14

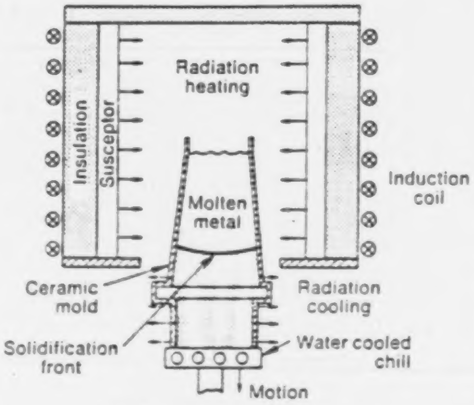
GRAPHITE DIRECTIONAL SOLIDIFICATION FURNACE


VIEWING PORT
UPPER WATER COOLED ELECTRODE
ARGON IN
GRAPHITE HELIX HEATER TUBE
ALUMINA CRUCIBLE
LOWER WATER COOLED ELECTRODE
SIGHT PORT FOR OPTICAL PYROMETER
ARGON IN
WATER COOLED PEDESTAL
FURNACE SUPPORT
TRAVERSE DIRECTION
TRAVERSE ATTACHMENT
WATER OUT
WATER IN

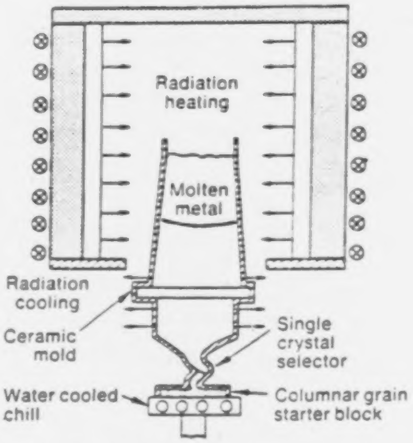
SOURCE: *Superalloys – Processing, Second International Conference.* **1972. Seven Springs, PA: American Society for Metals.**

Figure 2–15

DIRECTIONAL SOLIDIFICATION AND SINGLE CRYSTAL CASTING


Radiation heating
Insulation
Susceptor
Molten metal
Induction coil
Ceramic mold
Radiation cooling
Solidification front
Water cooled chill
Motion

Columnar grain casting process


Radiation heating
Molten metal
Radiation cooling
Ceramic mold
Single crystal selector
Water cooled chill
Columnar grain starter block

Single crystal casting process

SOURCE: *Alloys for the Eighties*. **Amax Incorporated. p. 69.**

SURFACE MODIFICATION

The use of directed energy and ion beam processing as well as new coating technology in modifying the surface properties of metals is attracting widespread interest.

LASER AND ELECTRON BEAM SURFACE TREATMENT

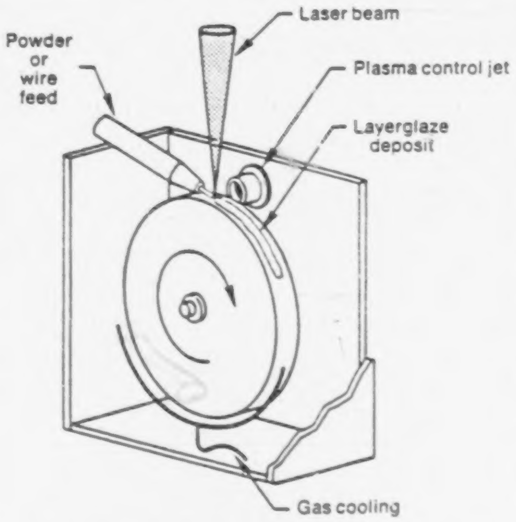
Rapidly-solidified surface structures have been produced by laser and electron beam surface melting techniques. In addition, surface alloying has been accomplished by making controlled additions of pre-alloyed powder, wire, or ribbon to the interaction or melt zone at the metal surface. One of the more interesting processes developed has been called "Layerglazing" or "Laserglazing" used for surface alloying, for bonding thin alloy layers to surfaces, and for building up rapidly-solidified bulk structures in near net shapes. The process is illustrated in Figure 2-16. The surface of the metal is scanned with a high-powered laser beam in order to melt a very thin layer of metal at the surface. The process is performed in a helium atmosphere to avoid oxidation. The melted layer is then self-quenched (cooled by heat transfer into the bulk of the sample) at a high rate (1,000 to 10,000°C per second), leaving a rapidly-solidified surface layer that has properties different from those of the underlying bulk metal. The microstructures of the resulting surface layer vary according to the heating input of the laser and subsequent cooling rates, and include refined dendritic structures, ultrafine mixtures of different phases, metastable phases, and amorphous solids.

Laserglazing has the potential to improve corrosion, erosion, and wear properties. For example, the process has been used to combat stress corrosion cracking in "sensitized" Type 304 stainless steel. This is achieved by adjusting the cooling rate to avoid the formation of a harmful carbide phase at the grain boundaries. Also, specific grades of high-speed steels used in metal cutting and grinding have been surface-hardened by layer glazing. The process has been applied to plasma-sprayed coatings to improve corrosion and erosion properties (by completely eliminating all surface porosity in the coating) and simultaneously to promote a sound metallurgical bond between coating and substrate. New breakthroughs are being further investigated in which hard particles are injected into the alloy substrate during layerglazing to produce a wear-resistant surface.

By delivering new material to the laser/surface reaction (melting) zone, surfaces may also be coated with any desired composition, with excellent bonding achieved between the coating and substrate because of contact with the melted surface. The other area of interest is the building up of an entire part by the continuous layerglazing of repetitive layers of material onto the surface, which are fused together by the intentional, slight remelting of the previous layer to produce a fully dense and sound body. Figure 2-16 illustrates this process for making a turbine disk. The individual layer thicknesses are on the order of 125 microns.

Figure 2–16

SCHEMATIC OF THE "LAYERGLAZE" PROCESS


Laser beam
Powder or wire feed
Plasma control jet
Layerglaze deposit
Gas cooling

- Material deposited in thickness characteristic of laser glazing
- Rapid quenching produces characteristic structure / properties of laser glazed alloys
- Process ideal for rotating parts with cylindrical symmetry

SOURCE: *Alloys for the Eighties.* Amax Incorporated, p. 69.

An advantage to making near net shaped parts by layerglazing is better homogeneity of the alloy components because the microstructures of deposited layers are much finer than they would be through conventional processing, and subsequent thermal treatments to modify properties should be more effective. Controlled residual stresses can be built in by the glazing process, and these may be desirable in certain applications. In addition, the process allows continuous on-line nondestructive evaluation for defects. When a defect is discovered, repair might be effected by reglazing or machining and reglazing. This technology is quite young at this time, but holds much future potential for making superior performance parts.

Besides the laser, electron beams can be used for layerglazing, but because the process is carried out in a vacuum, the surface effects are likely to be different. On the other hand, the laser is typically used in an inert gas atmosphere. Different surface-hardening effects have been observed using the two methods. The laser method has been more effective, possibly due to surface structure modification.

COATINGS

Great technological advances have been made in new kinds of corrosion- and heat-resistant coatings. Several techniques are in use to apply different types of coatings onto metal surfaces. These will be described briefly below:

- In chemical vapor deposition (CVD), a reactant atmosphere gas is fed into a processing chamber and decomposes at the surface of the workpiece. Many different types of metallic and nonmetallic coatings can be applied, including nickel, tungsten, chromium and metal carbides, silicides, oxides, and nitrides. The reactant atmospheres used include fluorides, chlorides, bromides, and iodides. Hydrogen is often used as the reducing agent. The advantages of the process include deposition of refractory metals at much lower temperatures than their melting points, and controlled density, grain size, and grain orientation of deposit. However, the process is somewhat limited by the high cost of some reactants and the low utilization of material. It is not a line-of-sight process.

- In physical vapor deposition (PVD), a metal or alloy is sublimed, i.e., vaporized and condensed onto a substrate. The source material is typically heated by laser beam, electron beam, or electrical resistance. The material is vaporized and then recondenses nearby onto the desired surface. The source material can also be sputtered by ion bombardment into the chamber atmosphere and subsequently onto the metal surface. It is a line-of-site process.

- In thermal spray coatings of metal and ceramics, material is deposited by flame spraying, plasma-arc spraying, and electric-arc spraying by line-of-sight deposition. Coatings are sprayed from rod or wire stock or from powdered material. The stock is melted by feeding it into the flame or high-temperature plasma (consisting of ionized gas). A high-velocity stream of compressed air or other gas propels the material onto the workpiece. Plasma-arc spraying has grown significantly in recent years because of more stringent coating requirements as well as superior performance. The electric-arc process utilizes metal wire and melts it by striking an arc between two oppositely-charged wires of the metal to be deposited. A compressed gas stream then deposits the coating.

A subset of thermal spray coatings, ceramic coatings, (including the metal oxides, carbides, silicides, borides, nitrides, and cermets) are applied for protection against oxidation and corrosion at room and elevated temperatures. These coatings can be applied by many different techniques, including spraying, dipping, plasma-arc spraying, and flame spraying. Parts can be dipped or sprayed in a ceramic slip and then furnace-fired to uniformly bond the coating. The other techniques simultaneously apply and bond the coating, in a process similar to the thermal spraying technique. The many ceramic coatings and applications cannot all be described here; they are, however, applied to improve heat-, corrosion-, and wear-resistance. Thermal barrier coatings based on zirconia (ZrO_2) compositions are used on parts in the hot sections of jet engines to prolong service life.

One of the more successful coating types for superalloy parts such as turbine vanes and blades is the MCrAlY type, where M is either Ni, Co, or Fe. The process was developed in order to combat oxidation occurring at high temperatures. The matrix is iron-, nickel-, and/or cobalt-based and contains a large amount of chromium as well as an intermediate amount of aluminum. Yttrium is added to help adherence and bonding.

The typical 2-to-5-inch blades can be coated with 0.003 to 0.010 inch of MCrAlY in about 2 to 8 minutes. A post-coating heat treatment at 1950° to 2000°F enhances bonding through coating/substrate interdiffusion (or interpenetration) for one to ten hours.

CoCrAlY coatings are recognized as having superior hot corrosion-resistance in the turbine engine, but NiCrAlY coatings exhibit better oxidation-resistance. The process can be automated and has been shown by Howmet Turbine Components Corporation* to give excellent service and performance; it is also cost-competitive with other processes for critical applications, such as in gas turbine engines and has become the most widespread process for coating parts for jet engine service. The service temperature can be increased so an alloy with less chromium behaves like an alloy with more chromium. It could lead to turbine-blade and vane alloys that have less chromium once these can be qualified for the jet engine.

---

*S. Shankar, D. E. Koenig, and L. Dardi, "Vacuum Plasma-Sprayed Metallic Coatings," Journal of Metals, October 1981, p. 13.

- Diffusion processes for coating involve the diffusion into the surface of the metal of some specific metallic element, such as chromium, in order to impart surface hardness, wear-resistance, or corrosion-resistance. One example is the chromizing of common steel, in which the surface chromium content is increased. It is not a line-of-sight process. Other examples of commercialized processes are:

  --the Dilex System, in which a ferrous part is treated in a molten lead bath containing the element to be diffused in (e.g., chromium). Because of the small solubility of iron in lead, the workpiece is hardly affected. Also because of low solubility of lead in iron there is no contamination of the workpiece.

  --The TD or Toyota Diffusion process, in which a ferrous part is treated in a molten salt bath in which a ferroalloy such as ferrochrome is dissolved in order to impregnate the surface.

- Electroplating, such as conventional chromium electroplating, is often used to apply a thin chromium layer on a part for corrosion-resistance. The part is immersed in a chromium-containing solution as an electrode. When direct current is passed through the system, chromium comes out of solution and plates on the part, which is then lifted out of the solution. This is not a line-of-sight process.

- Hot dipping processes such as galvanizing and aluminum coating are used to coat ferrous parts with zinc and aluminum, respectively. The workpiece is dipped in a molten metal for the principal purpose of enhancing corrosion-resistance. It is not a line-of-sight process.

- Sputtering is a process that can be used for cleaning or etching a surface and/or for coating the surface with another material and is a line-of-sight process. The surface and/or the other material are subjected to bombardment of high-energy particles such as heavy inert gas ions (e.g., argon), which dislodge the metallic material. In the case of sputter coating, the dislodged material is then redeposited onto the workpiece. A variant of sputter coating is ion plating, in which the substrate or the depositing film is modified during the coating process by high-energy particles to enhance adhesion. It is a line-of-sight process.

ION IMPLANTATION

This is a process in which ions are embedded into the workpiece rather than deposited onto the surface by using high-energy ion beams. It is a line of sight process. The most important applications have been in the semiconductor industry, for doping materials with specific impurities with precise spatial and concentration control. In these applications this process is fully commercial. It is, however, in the early development stage with respect to the enhancement of wear- and corrosion-resistance. The process can also lead to the formation of unusual phases.

Ion implantation has been used to apply nitrogen and carbon to cobalt-base cemented carbides. Another application is in the implantation of nitrogen in tool steels. In both cases, the life of the workpiece is lengthened. Other elements such as chromium or nickel could be ion implanted, but the resulting properties do not depend on the type of ion implanted as much as on its mechanical deformation of the matrix at the surface when implanted. Therefore the choice of an implanting ion is based on its mechanical effect in the host material, not on its own inherent oxidation or corrosion-resistant properties. To be effective in imparting corrosion resistance, the ionic density must be on the order of 1017 per cm. (compared to only 1010 per sq. cm. for semiconductors). Commercial equipment capable of this higher beam density has yet to be developed. Most of the pioneering work on ion implantation has been done in the United Kingdom but substantial research is also being carried out in the United States.*

CLADDING

Cladding is a surface coating technique that involves bonding a sheet of another alloy that may be more corrosion-resistant or wear-resistant than the underlying metal. The clad metal can be produced by a number of methods. One method practiced is to bond the two sheets together by hot rolling or roll bonding; the high pressure and heat cause the bonding action. Bimetallic tube has reportedly been cast from the melt, but details of this process were not available. The cladding thickness is typically much greater than with other coating methods. Cladding allows precise control of composition and thickness, and complex multilayer systems can be produced. However, fabricated parts and brittle materials cannot be clad. Applications include pressure vessels for the petroleum, chemical, pulp and paper, and other process industries; automobile bumpers using a clad layer of stainless steel over aluminum to reduce weight (50 percent reduction from conventional steel and 35 percent from high-strength steel); automotive trim (again using stainless on aluminum); aircraft firewalls; integrated circuit lead frames (ferritic stainless between two copper layers); nuclear power plant piping; steam suppression pools; and deep hold tanks in ships.

Various metals can be clad together, such as stainless on aluminum, stainless on carbon steel, titanium on carbon or stainless steel, zirconium on carbon or stainless steel, and copper on stainless steel. For example, Lukens Steel Company now clads large steel plates with corrosion-resistant alloys such as the nickel-base Inconels 600, 625, and 800; Incoloy 825; and the cupronickels, in widths up to 178 inches, lengths to 480 inches, and thicknesses to 8 inches. Welding of clad plate is now feasible by a two-step process and is very well described in Luken's clad steel brochures.* The technique usually bevels both ends to be buttwelded to form what looks like a V with the clad side at the bottom of the V. A welding electrode of the base metal is first used. Then a higher-alloy electrode is used on the cladded side. This technique is used for Cu or Cu/Ni clad alloy or carbon steel, and Ni alloy or Cr clad steels.

---

*D.I. Potter, M. Ahmed, and S. Lamond, "Metallurgical Surfaces Produced by Ion Implantation," Journal of Metals, August 1983, p. 17, and, K. V. Jata, E. A. Starcke, Jr., "Surface Modification by Ion Implantation -- Effects on Fatigue," Journal of Metals, August 1983, p.23.

In summary, surface modification techniques represent a well-established technology, and work is continuing to improve them in order to enhance the overall performance of the parts. Most of the techniques are in use commercially.

The processes can be subdivided into: 1) those leading to thick surface layers, i.e., cladding, powder metallurgy techniques, thermal spraying, and surface alloying; 2) those leading to thin surface layers, i.e., chemical vapor deposition, physical vapor deposition, sputtering, and ion plating; and 3) ion implantation, in which no surface layer is created but ions are imbedded below the surface of the workpiece.

Most of these processes lead to enhanced wear-, corrosion-, and/or thermal oxidation resistance.

A number of surface alloying and modification techniques are currently in the research and development stage. (Lasers and electron beams are now used commercially by the automotive industry to harden the surfaces of engine components, but this does not involve net changes in composition.) Surface modification and alloying have now been demonstrated to have a dramatic effect on many surface-related properties, such as corrosion, oxidation, friction, hardness, wear, fatigue, and catalytic reactivity. The structure and composition control obtainable have the potential to improve understanding of the influence of microstructure on materials surface properties. The technology has been applied to the laboratory production of near net shape parts, such as in the layerglazing process. This process appears to have interesting possibilities for improving properties and reducing the overall raw material input.

FUTURE ADVANCES IN METAL PROCESSING TECHNOLOGY

So far this chapter has given the reader an overview of the basic processes involved in producing many types of products (from simple billets, bars, and plate products to complex, high-performance jet engine turbine blades and disks) by precision forging and casting.

The most important continuing technological advancement is the production of near net shape parts either by casting, forging, or powder metallurgy. Most of these technological improvements have involved high-performance and expensive alloys as well as parts for the aerospace industry.

---

*Lukens Steel Company, Fabrication of Lukens Clad Steels, Coatesville, Penn.

The advances that will be significant in their impact not only on materials usage but also on cost of parts produced will be outlined below. Some other important issues will be discussed in subsequent chapters.

MELTING TECHNOLOGY

The trend toward clean metal technology will continue. This involves the ongoing search for better ways to refine the metal to remove such deleterious impurities as sulfur, phosphorus, bismuth, and antimony. The major jet engine makers have set a goal to double the service life of parts made of IN718 and Waspaloy by using cleaner metal. The vacuum-melting technologies (VIM, VAR, ESR, EBR) will become more pervasive throughout the metallurgical industry. The AOD process will continue to expand its usage not only upward into high-performance alloys but also downward to alloy and tool steels and carbon steels.

A new technique called VADER (Vacuum Arc Double Electrode Remelting) uses two consumable electrodes of the metal to be melted and refined. The process consumes 40 percent of the energy of the VAR process and operates at three times the melt rate at which VAR operates. The electric arc is established between the two metal electrodes, melting the metal and allowing it to fall as droplets into a crucible. The crucible is withdrawn at a continuous rate to enable continuous casting. VADER can produce fine-grained superalloy ingots that can be readily hot-worked, and it has potential as an alternative to powder metallurgy for working with complex, difficult-to-fabricate high-performance alloys such as RENE 95, AF115 and MERL 76. One of the differences that improves VADER products is that the solidification occurs under a lower temperature gradient than that for VAR products, resulting in reduced thermal stresses (which can cause cracking in VAR ingots) and finer grain sizes that permit greater ductility and workability. The process is still in the laboratory but it is the latest development in vacuum-melting technology and will help improve both cleanliness and the performance of alloys at a lower cost.

CASTING

In the area of casting technology, precision-cast parts are making inroads into areas where forging and welding were formerly used for complex shapes. For example, large jet engine casings can now be cast as one piece. The trend in casting is toward larger and larger parts (one company can cast superalloy parts up to about 500 pounds). This will lead to cheaper parts because the former forging and welding operations were labor-intensive and costly. Eventually, entire sections of engines are expected to be integrally cast.

The current range of buy-to-fly ratios for the casting of blades and vanes (that is the ratio of the weight of input material to the weight of final part) stands at about 1.2:1 in directional solidification, as compared to

5 to 6:1 by conventional casting. In addition, increased use of hot isostatically-pressed castings is expected, since excellent improvements in performance have resulted from HIPing INCO 718 alloy parts such as burner nozzles and casings for jet engines. This is a lower-cost technique than conventional methods. The fatigue strength of an alloy 718 casting can be raised from 45,000 psi to 65,000 or 70,000 psi by HIPing treatment.

POWDER METALLURGY (P/M)

The use of hot isostatic pressing will continue to be developed for many different types of alloys and parts. Great potential lies in combining HIPing of powders into preforms that can be isothermally forged to near net shape or net shape parts.

HIPing is being used for the rejuvenation of turbine vanes and blades,. principally alloys Udimet 500 and 700 in land-based gas turbines and Mar M 200 in jet engines. The original strength properties are usually recovered by healing minor creep damage, doubling the life of parts, but the practice is still conducted on a small scale. The process operates by plastic deformation and densification to close clean microcracks that form in the material. Chromalloy-Oklahoma states that HIPing can help engine manufacturers because it can reduce property scatter, thereby lending more credibility to design, either by raising allowable stress levels or by extending the period for overhaul. (This sentiment did not seem to be shared by the major engine manufacturers, however, since rejuvenation of worn parts is still not widely practiced.)

A new processing route for P/M parts has been developed based on cold isostatic pressing (CIP) followed by sintering and, if necessary, hot isostatic pressing. Tooling for CIP is relatively inexpensive compared to HIP. The use of HIP for densification of sintered parts would not require a "can" as in conventional HIP, and is therefore less expensive than proceeding directly from powder. A complex shaped part can be produced this way if cold compactible powder is available. There is also flexibility in alloy design. For instance, "mechanical alloys"* can be created by ball milling alloy powders and oxide powders together with other additives before densification and sintering. In the CIP process, one could also use rapidly-solidified powders. The procedure is also compatible with oxide dispersion strengthening (where specific metallic oxide additives are used to confer strengthening to the alloy). The CIP process is being used commercially for titanium, aluminum, and copper alloys, but we do not believe it is used commercially at present for superalloys and stainless steels. CIPed parts need not be restricted to aerospace uses; for example, they are used in the chemical process industry for valves and instruments and for orthopedic implants.

---

*Mechanical alloying involves a dry milling of alloy powders and an inert yttrium oxide powder additive together. The particles plastically deform, flatten against one another and then weld to become a composite. These composites fracture and reweld as the process continues. The process sets up a kneading action which refines the powders and bonds the oxide dispersion hardening agent to the alloy. The resulting powder has a typical particle size of 0.5 micron with 300 Angstrom size oxide particles dispersed in the powder particles. These alloys have been commercially used in limited quantities and were introduced by INCO under the names of MA 754 and MA 6000E. MA 754 has a nominal composition of Ni-15CR-4.5Al-2.5Ti-4W-2Ta-2Mo-0.5C-0.15Zr-0.1B-1.1Y_2O_3.

Research also continues on eliminating post-HIP heat treatments, which can improve the final properties of the part and lower HIPing cycle time and costs. Rapid cooling after HIPing has demonstrated improvements in yield strength and low cycle fatigue strength in some instances; continuing work is attempting to improve the productivity and control property optimization more tightly, i.e., increase reproducibility. HIP systems are expensive and the trend is toward making them larger in the future. An estimated $10 million of HIP equipment was in place in 1981 in the United States, with the potential to reach $75 million by 1985. A small HIP unit (or HIP press) for R&D purposes could cost $80,000, and a large production system would require at least $1 million (much more for a special customized system).

Another area where HIP use might be increased in the future is in the oil country industry, in products for drilling and pumping equipment. These applications involve the cladding of internal valve faces by HIPing a superalloy powder overlay onto a forged valve body. The overlay could be Incoloy 800 and the valve body underneath could be 4130 alloy steel.

In addition, alloy powder could be encapsulated and extruded into consolidated bar stock. Both of these HIPing applications are being pursued by Cameron Iron Works of Houston, a major parts supplier to the oil country industry. After purchasing Kelsey-Hayes' HIPing facility in Brighton, Michigan, Cameron is positioned to supply sophisticated powder metallurgy parts to both the oil country and aerospace industries.

FORGING

The more exotic types of forging, such as Gatorizing and hot die forging, are currently restricted to a few high-performance alloy parts that cannot be fabricated any other way to obtain the same performance. These processes are cost-effective for high-cost alloys and parts but would not be cost-effective in making stainless or alloy steel parts. The trend is toward further automation of these processes. There is potential for future diffusion of these technologies, which would allow the production of cheaper, less high-performance parts, but this is likely to be a slow evolution.

The major technical advance to be made will be to adapt the state of the art isothermal forging/superplastic forming to further approach the final part net shape. This aim will be increasingly facilitated by CAD/CAM systems (computer-aided design and manufacturing) in the design of parts and dies as well as in advances in inspection technology as described below, in order to overcome the limitation of the sonic shape needed for inspection purposes.

Research should also continue to improve inspection and quality control methods to produce parts closer to final shape. Currently, the minimum shape that can be inspected using current sonic techniques is shown in Figure 2-17 as the sonic shape or sonic envelope. There is a certain thickness of material over the final shape dimensions that is necessary for sonic testing to detect flaws in the entire body of the finished part. The envelopes for conventional forging and isothermal forging are shown in the figure. If new cost-effective inspection or NDE techniques could be developed that would eliminate the sonic shape limitation, further reductions in scrap generation from machining and lower overall costs per part could be realized.

Another advance likely to become more prominent in the future is the use of powder preforms for forging (these are already being used for isothermal forging operations). For example, the Consolidation by Atmospheric Pressure (CAP) process of Universal Cyclops is being used to make consolidated powder preforms. This process places alloy powder into a glass (Pyrex) mold, degases it, and seals the mold. The mold is heated in a furnace for 8 to 24 hours. The glass mold softens, and the only pressure then acting on the powder is the atmospheric pressure around it. The sintered product is about 98 to 99 percent dense, and it can be further hot- or cold-worked to close to 100 percent density. The product is usually sold as a billet to the forgers.

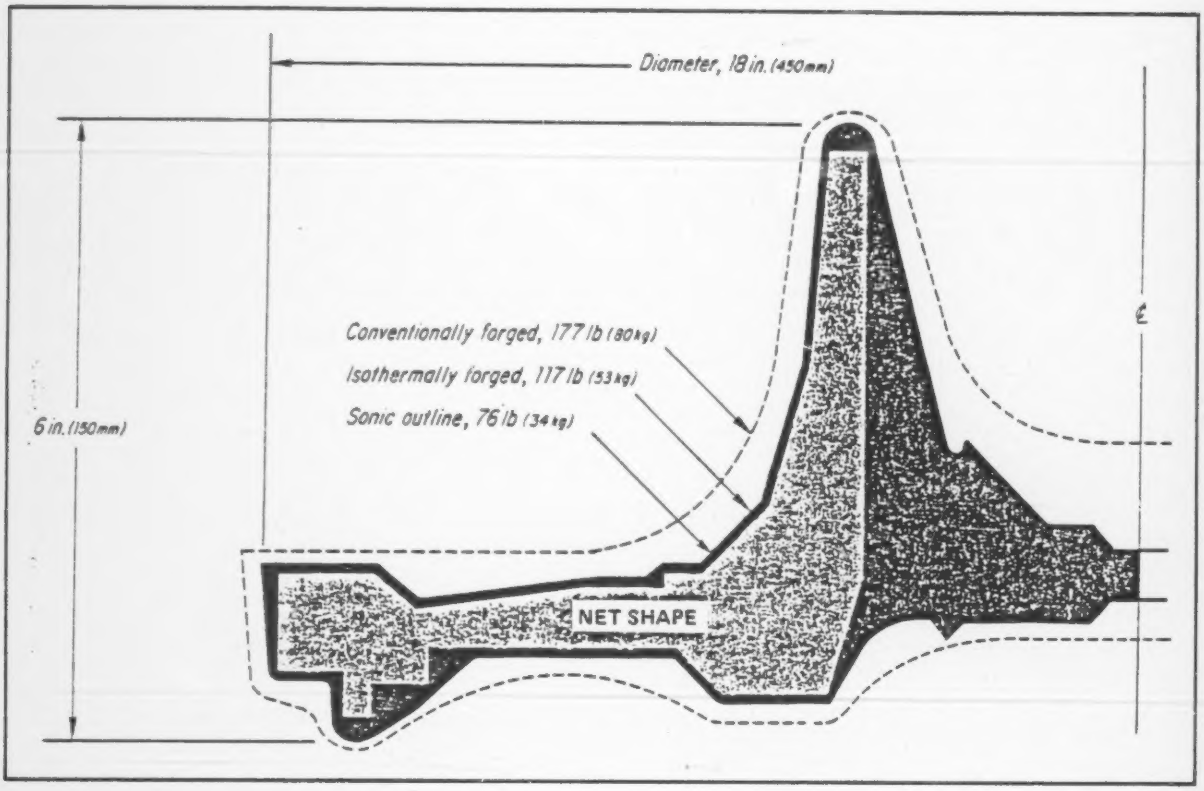
Another similar process developed at Kelsey-Hays is like the CAP process but involves the containment of powder within a ceramic matrix. The sintered powder preform can then be forged by conventional means. Further development of these types of processes is expected to improve the use of forging powder preforms.

There is expected to be growth in the use of HIP for forging preforms. The procedure has been practiced commercially for making isothermal forging preforms. HIPing of powder to near net shapes for critical parts does not yield the required reliability, but HIPing will be used to provide starting materials for other metal-working processes.

Superplastic-forming and diffusion-bonding have been developed for the commercial production of titanium parts, but the process has not yet been implemented for superalloys. R&D work is being conducted in the area of superalloys, however, because of the economies that have been gained in titanium. For example, in the making of titanium fan blades for the front sections of jet engines, conventional processing for making a solid blade had a buy-to-fly ratio of 6:1 or 9:1. By using superplastic forming/diffusion

Figure 2–17

DIFFERENT ENVELOPES ASSOCIATED WITH DIFFERENT FORGING PROCESSES


Diameter, 18 in. (450mm)
6 in. (150mm)
Conventionally forged, 177 lb (80kg)
Isothermally forged, 117 lb (53kg)
Sonic outline, 76 lb (34kg)
NET SHAPE
℄

SOURCE: *Production to Near Net Shape Source Book.* 1983. American Society for Metals. p. 115.

bonding, a hollow blade can be produced that cuts the ratio to 1.2:1 or 1.6:1. This has cut the fly weight by 12 to 40 percent with the same performance and has markedly decreased the amount of input material.

Superplasticity is a phenomenon that occurs when metal is heated to a certain temperature and deformed. Rather than being stretched just 10 to 30 percent, metals such as titanium will stretch as much as 2,000 percent. Diffusion bonding occurs at specific temperatures and pressures between two pieces to be bonded. When pressed together, the atoms of the two parts will diffuse into the adjacent piece, forming a single piece with a joint strength equivalent to the original piece. These processes have eliminated the use of fasteners in the production of complex aircraft parts, and in many cases have cut costs by 50 percent and enabled weight savings per part of 30 percent or more.

RAPID SOLIDIFICATION PROCESSING

Rapid solidification has opened the field of new alloy development through the combination of structure control and its direct effect on many properties, as well as its ability to improve the hot and cold workability of the alloys. For example, a new alloy RSR185, a nickel-base alloy containing 14.3 percent Mo, 7 percent Al, and 6 percent W, is of interest in turbine airfoil applications. This kind of Ni-Mo-Al alloy has shown an increase of 150°F in operating temperature capability over the existing MarM200 (nickel-base, 9Cr, 10Co) alloy. Use of this alloy in discs depends upon its low cycle fatigue properties.

Commercial production of rapidly-solidified superalloy material has reached the level of a few thousand pounds per year; so far, only traditional alloy compositions have been produced. At least 10,000 discs made from rapidly-solidified material are now operative in jet engines.

So far, the trends in development work have been to obtain equivalent or better properties using reduced amounts of critical metals. However, the technology enables higher solubility of additive elements than in conventional processing. With the continuing push for higher performance, there is also the possibility, in some cases at least, that the levels of critical metals such as cobalt and chromium may actually increase rather than decrease because of the need to obtain higher corrosion-resistance and higher operating temperatures.

One area of powder consolidation receiving increased attention is dynamic or shock-wave consolidation.* The technique has been known and investigated for nearly 20 years, particularly in the Soviet Union. A shock wave is passed through the powder. This shock wave is generated either by an explosive or by impact of a high-velocity projectile against the material. Bonding is produced by the heat generated from the explosion through deformation at the

*See *Journal of Metals*, October 1981, p. 21.

particle interfaces; temperatures high enough to cause localized melting are reached. However, cooling rates are also extremely rapid, similar to RSP rates. Continuing development work will seek to apply RSP to more types of parts.

The main avenues for future R&D will be in the following areas:

- Continuing work on superalloys that have radically different compositions than conventional alloys.
- Improving process control in both powder manufacturing, production scale-up, and powder consolidation by such methods as forging, rolling, extrusion, vacuum hot pressing, HIPing, and dynamic consolidation (shock-wave compaction). A key element is to maintain lower temperatures during consolidation so as not to lose the metastable structure obtained by rapid cooling. Dynamic consolidation has many advantages. Cleaner powders needed to avoid foreign inclusions are produced through the use of cleaner feedstock, better melting practice, no melt contact with ceramics, and all-inert powder handling. A major concern is the high cost and limited availability of RSP materials, which will restrict their commercial utilization in the future.
- In the automotive area, development of new RSP iron-base alloys along with advanced forming techniques for low-cost components in engines. For example, a combined forging and extrusion process is needed to produce integrally-bladed turbine wheels.
- Producing amorphous metal as a pathway to obtaining new microstructures with improved properties.

SURFACE TREATMENTS, COATINGS, AND CLADDING

With the exception of ion implantation, all of the processes previously described are commercially practical. Major developments are aimed at improving their process economics.

Ion implantation, however, is unique and appears to have major potential. The principal barrier is the development of commercial high-ion density implantation equipment. The principal economic barrier is the cost of such equipment.

Coatings and claddings are expected to expand greatly in the future in diversity and utilization. Thermal barrier ceramic coatings and the NiCrAlY, CoCrAlY, and FeCrAlY oxidation-resistant coatings are among the most noteworthy. The type of coating or cladding technique to be used will tend to vary on a case-by-case basis.

SHAPE WELDING

An interesting technology developed by the German steelmaker Thyssen AG produces an all-weld metal component out of steel. The part is essentially built up around a starting mandrel or shell by numerous layers of welded metal through the submerged-arc welding process. Shape welding has been able to produce parts that can replace large forgings on a shorter delivery schedule (two-year delivery time for forging versus four months for shape welding). The process is being applied to making large pressure vessels, boilers, rotors, and turbine shafts. The mechanical properties have been found to be equivalent to or better than parts made by conventional processes such as forging. Chemistry control and uniformity are also much improved. A secret of this success has been the use of welding wires (the source material) with low carbon content and fluxes having low residual impurities.

The present production equipment is capable of making components up to 100 tons in weight. The materials used in the process are mainly high-strength steels such as the 2.25 Cr-1 Mo type and the ASTM A508 Class 3 steel, among others.

The technique can be used not only to produce motor shafts but also to build up the blades on those shafts. This eliminates mechanical fastening and potential problems arising from intercrystalline corrosion. Some have speculated that shape welding could be used to do anything that is now being done with forgings. So great is the confidence in the process that equipment is now in place that could produce shape-welded components up to 700 tons in size.

AUTOMATION AND ROBOTICS

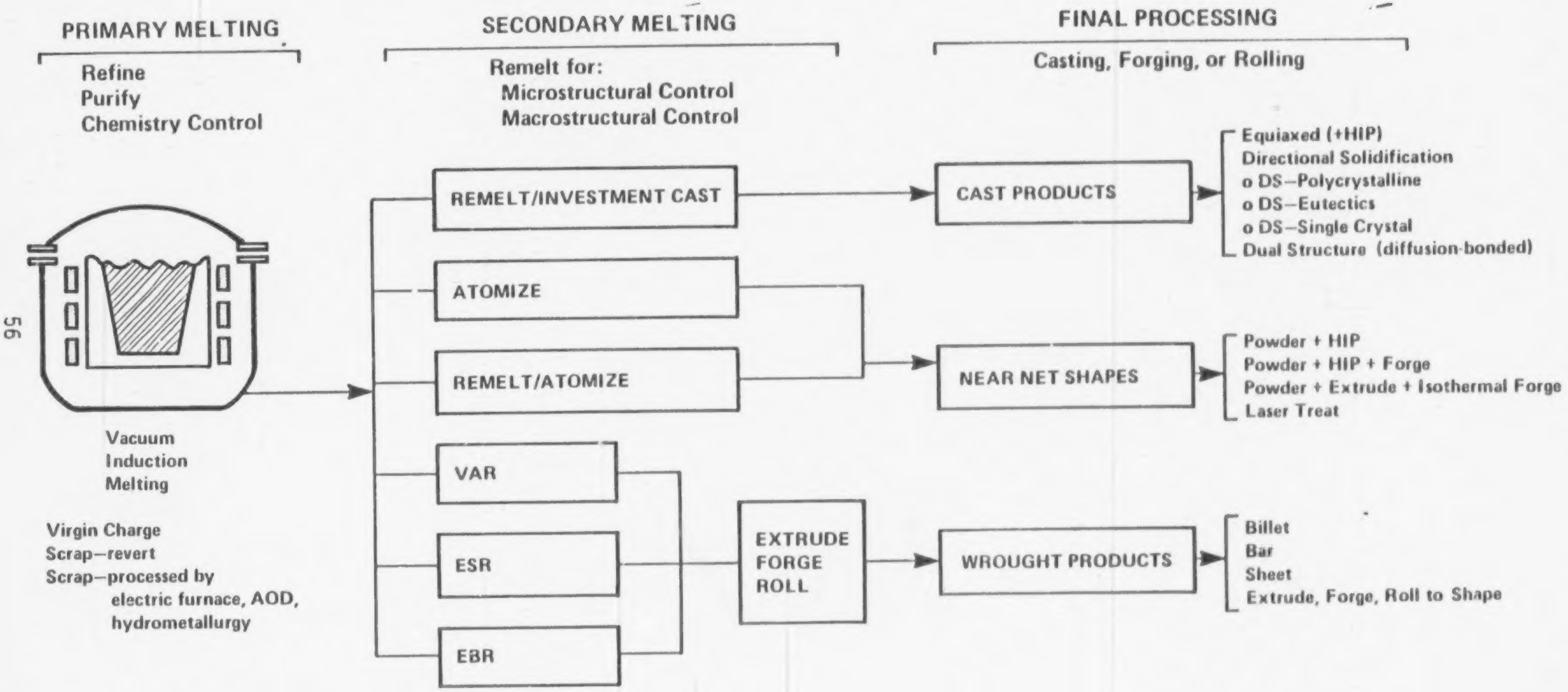
Automation has already been implemented in several areas, in conventional forging and in isothermal forging and to a limited extent in vacuum melting technology. Foundries are moving into robotics for the mass production of casting molds, although the casting process itself still requires operators. Some of these operations, such as the vacuum melting of master alloys for superalloy production, are complex since they must deal with compositions with over a dozen alloying elements and where proper slag and impunity control is very critical. Software to handle these complex conditions in vacuum melting is not yet adequate.

SUMMARY

In the metals fabrication field today, there are a great number of processes that can be utilized, many of which are in the developmental stage. Therefore, a thorough enumeration is not feasible in this primer. We exemplify this complexity by showing, in Figure 2-18, the alternative processing routes for VIM ingots.

Figure 2–18

ALTERNATIVE PROCESSING ROUTES FOR VIM INGOTS


PRIMARY MELTING
Refine
Purify
Chemistry Control
SECONDARY MELTING
Remelt for:
Microstructural Control
Macrostructural Control
FINAL PROCESSING
Casting, Forging, or Rolling
REMELT/INVESTMENT CAST
ATOMIZE
REMELT/ATOMIZE
VAR
ESR
EBR
EXTRUDE
FORGE
ROLL
CAST PRODUCTS
NEAR NET SHAPES
WROUGHT PRODUCTS
Equiaxed (+HIP)
Directional Solidification
o DS–Polycrystalline
o DS–Eutectics
o DS–Single Crystal
Dual Structure (diffusion-bonded)
Powder + HIP
Powder + HIP + Forge
Powder + Extrude + Isothermal Forge
Laser Treat
Billet
Bar
Sheet
Extrude, Forge, Roll to Shape
Vacuum
Induction
Melting
Virgin Charge
Scrap–revert
Scrap–processed by
electric furnace, AOD,
hydrometallurgy

SOURCE: *Metals Progress,* October 1982, p. 52.

The major process developments are taking place in the high-cost, high-performance end of the materials spectrum, with the majority of these being applied to the superalloys for aerospace and military uses. It will take some time before the latest fabricating techniques for making jet engine components are used for fabricating everyday items out of stainless steel and alloy steel. However, examples of powder metallurgy and, more recently, shape welding have been applied to the more common varieties of alloys. Some of the present state-of-the-art commercial processes have taken 10 or 20 years to develop, and they are still only cost-effective for the most expensive, high-performance alloys and components. The diffusion of technology is expected eventually to have positive effects on the more common types of alloys, but this will take some time.

3

SPECIFIC END-USE APPLICATIONS

GENERAL INTRODUCTION

This chapter reports on several key end uses of interest for their future impact on the demand for cobalt, chromium, and manganese. These end uses include areas where new processing technologies are heavily involved (e.g., gas turbine engines) and emerging non-aerospace uses that could experience substantial future growth in demand for critical metals (e.g., oil country tubular goods for deep sour wells). More traditional applications that will eventually be influenced by the diffusion of state-of-the-art fabrication technology from the aerospace industry include those utilizing constructional plate steel.

To put these end uses into perspective, several tables follow that indicate U.S. cobalt, chromium, and manganese consumption by intermediate end use. A large percentage of total cobalt consumption is accounted for by superalloys (6.3 million pounds). Of this quantity, 2.9 million pounds go into wrought nickel-base alloys, 0.4 million pounds to cast nickel-base, 1.3 million pounds to wrought cobalt-base, and 1.7 million pounds to cast cobalt-base alloys. Chromium demand is dominated by stainless steel. About 15,800 short tons of high-purity chromium metal ($4.00 per pound) go into superalloys; the rest of the chromium is added as ferrochrome. Manganese is dominated by steel uses; essentially none is used in superalloys. The trends to be discussed for constructional steel plate (a large component of carbon and alloy steel use of manganese) also apply to all areas of manganese use in steel.

It should be noted that material savings figures cited refer to input raw material to the melting operation and not to savings at the final part stage. This also assumes the present status of incomplete scrap recycling. (If all scrap could be recycled then there would be no actual savings in material from new technology in fabrication since any waste using an existing process could be recovered and reused.)

Table 3-1

U.S. COBALT CONSUMPTION BY USE IN 1980
(Million Pounds)

Use	Consumption
Superalloys	6.3
Tool Steels	0.3
Cutting and Wear-Resistant Materials	1.3
Hardfacing and Welding Materials	0.6
Magnetic Alloys	2.3
Catalysts	1.7
Other Chemicals*	2.2
Other	0.6
Total	15.3

*Reporting methods changed in 1979, so data for earlier years may not be comparable.

SOURCE: U.S. Bureau of Mines, Mineral Industry Surveys.

Table 3-2

U.S. CHROMIUM CONSUMPTION BY END USE IN 1980
(Short Tons of Ferroalloys and Metal, Gross Weight)

Use		Consumption
Steel:	Carbon	5,902
	Stainless and Heat-Resisting	296,769
	Full-Alloy	69,312
	High-Strength Low-Alloy and Electric	11,867
	Tool	4,369
Cast Irons		9,059
Superalloys		15,764
Welding and Hardfacing Rods		1,688
Other Alloys		3,371
Miscellaneous		1,627
Total		424,430
Cr Content		252,493

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various issues.

Table 3-3

U.S. MANGANESE CONSUMPTION BY END USE IN 1980
(Short Tons, Gross Weight)

End Use	Ferromanganese High Carbon	Ferromanganese Medium and Low Carbon	Silicomanganese	Manganese Metal
Steel				
Carbon	601,743	93,834	92,196	5,706
Stainless and Heat-Resisting	10,980	840	5,456	2,353
Full-Alloy	79,985	13,963	32,873	861
High-Strength Low-Alloy	51,753	11,838	8,319	1,006
Electric	2	73	69	3
Tool	471	31	42	167
Unspecified	640	111	1,015	1
Total Steel	645,574	120,692	139,970	10,097
Cast Irons	15,317	1,050	11,695	8
Superalloys	232	W	W	193
Alloys (excludes alloy steels and superalloys)	1,574	451	2,576	14,112
Miscellaneous and Unspecified	3,492	694	1,576	682
Total Consumption	666,189	122,887	155,817	25,092

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, 1980.

GAS TURBINE ENGINES

INTRODUCTION

Gas turbines are major consumers of chromium and cobalt. Because of the high added value of gas turbine parts (up to 100 times the value of the raw materials), the price elasticity of demand for chromium and cobalt is low; nevertheless, the unusually high increase in cobalt prices in the 1978-1982 period led to conservation, mainly through selection of alternative alloys low in cobalt. In the case of chromium, however, conservation by substitution has not been as effective. For both elements, changes in process technology are the major source of conservation.

The major application for gas turbines is in jet engines. Other major uses are in electric power generating (peak) units for utilities and in land/offshore-base prime movers.

For a typical jet engine like the Pratt and Whitney F-100 for fighter aircraft, the weights of different contained metals are as follows:

	Pounds	Percent
Titanium	5,366	40.3
Nickel	5,204	39.1
Chromium	1,656	12.4
Cobalt	910	6.8
Columbium	171	1.3
Tantalum	3	0.02
Total Weight	13,310	99.92

The typical contents of chromium and cobalt in electric power generating units, per 1,000 megawatt generating capacity, are 100,000 and 50,000 pounds, respectively. These are also the estimated U.S. demands per year, since addition of peak power gas turbine units is on the order of 1,000 megawatts per year.

Land and off-shore gas turbines are typically small and vary in size. Demand is about 100 units per year in the United States. Thus, the total chromium and cobalt demand for these applications is relatively minor compared to that for jet engines and industrial gas turbines.

In total, the 1980 net demand of chromium and cobalt in the United States for all superalloy applications was about 6.3 million pounds of cobalt, of which one-half to two-thirds went into gas turbine engines. Chromium demand in superalloys amounted to 31.6 million pounds, most of which again went into gas turbine engines.

Fabrication technologies for gas turbine components include:

Casting - A. Processing:

- precision, conventional
- precision, large castings
- precision, directionally-solidified

B. Post-casting treatments

Forging - A. Stock from which they originate:

- wrought
- powder preforms

B. Processing:

- conventional
- isothermal

Powder Metallurgy - A. From:

- conventional powder
- unusual powder

B. Processing:

- hot isostatic pressing
- others

CASTING TECHNOLOGIES

PRECISION CONVENTIONAL

The precision investment casting process has been used since the earliest times of the jet age. Because of the need to add gates and risers, which ensure complete filling of the mold, as little as 40 percent of the molten metal poured into the mold results in usable castings. However, these castings are very close to their final shape (only 5 to 10 percent of the material is removed during the final machining and finishing operations).

One of the major advantages of casting processes is the ability to use alloys that are not amenable to being hot-worked. Often these alloys are stronger, and therefore their material content is more effectively utilized.

Most of the scrap generated in casting is "immediate revert" -- that is, it can be recycled without further processing. Since it is recycled in the same shop in which it is generated, segregation and identification are simple matters. Therefore, one can safely assume that virtually all material poured from the melting furnace is sooner or later utilized.

This is not necessarily the case for old scrap -- those parts that have been in service and are retired. There have been tremendous strides in recent years toward increasing the utilization of old scrap. For instance, after retirement, more and more pedigreed parts are returned to their originator and recycled.

PRECISION LARGE CASTINGS

Recent trends have yielded precision castings that weigh up to 500 pounds each (compared to the typical 10 pounds of old castings). There is a dual advantage in this development. First, a larger portion of the gas turbine is fabricated by casting rather than the less material-efficient forging process.* Second, substantial assemblies are fabricated in a single piece, thus eliminating the need for brackets and fasteners. It is estimated that some of these assemblies consist of only 7 percent of the original input material. In the case of casting, they consist of at least 20 percent of the original material.

PRECISION DIRECTIONALLY-SOLIDIFIED CASTINGS

In the case of conventional castings (large or small), the major weakness at service temperature derives from the grain boundaries. Directional solidification leads to very large grains whose boundaries are aligned with the axis of the component. Grain boundaries can also be completely eliminated, thereby enabling fabrication of components that consist of a single crystal. This allows the elimination of the usual grain boundary-strengthening elements like zirconium and hafnium, which greatly simplifies the alloy composition. There is no problem with the metastable crystal structure changing while undergoing stresses in service. Any stresses large enough to cause reversion of the structure would be enough to damage the part and take it out of service.

A comparison is shown below of two alloy compositions; one is Alloy 454, which is cast as a single crystal blade, and the other is D.S. MAR-M200+ Hf, directionally-cast. The numbers are in weight percentages.

---

*Casting is more materials-efficient than forging because most of the revert can be immediately and completely reused. In some cases casting approaches near net shape better than forgings, and forging flash and machined turnings usually pick up contamination and must be remelted and refined before reuse. Forging turnings may have to be downgraded for some other use.

	Ta	W	Cr	Al	Ti	Cb	Co	Hf	C	B	Zr	Ni
Alloy 454	12	4	10	5	1.5	--	5	--	--	--	--	Bal.
D.S. MAR-M200+ Hf	--	12	9	5	2	1	10	1.8	0.14	0.02	0.08	Bal.

Alloy 454 in testing showed a 25° to 50°C higher operating temperature over the directionally-solidified alloy. The alloys tend to have higher strength than more conventional alloys. This kind of temperature gain translates into a threefold improvement in life at normal operating temperatures (or else an equivalent service life at the higher temperatures).

POST-CASTING TREATMENT

All castings are affected by a certain degree of porosity, which adversely affects some critical properties. In recent years, this problem has been largely alleviated by subjecting as-cast parts to hot isostatic pressing. This technology has diffused rapidly and is now fully commercial.

Since the cast component is consolidated, there is no need to use a "can" or enclosure; therefore, tooling and labor costs are lower through hot isostatic pressing than in the case of conventional powder processing (see below).

The post-casting HIP treatment increases the average stress-rupture life by 100 percent and the fatigue life by 800 percent in hafnium-modified B-1900 and hafnium-modified IN792, both nickel-base superalloys.*

REJUVENATION OF SERVICE PARTS

After service, some cast parts can be repaired, mainly by welding and recoating, thus extending their useful life.

There are contradictory reports on the ability to extend life of service parts by hot isostatic pressing. We understand that, in ideal cases, life can be so doubled. On the other hand, this treatment appears to be far from universal, and probably limited to the repair of minor creep damage. Hot isostatic pressing of service parts should not be confused with a similar treatment of as-cast parts (discussed above), which is universally accepted as an effective life-extending process.

FOREIGN COMPETITION

The United States is at the forefront in casting technology and is the uncontested leader in the art of large precision casting.

---

*Metals Progress, April 1983, p. 23.

FORGING

SELECTION OF FORGING STOCK

Closed-die forging is extensively used to fabricate gas turbine components, ranging from small buckets to large fan blades and very large discs. Usually the starting stock is wrought -- that is, it consists of a bar or billet that has been processed by hot-working an ingot. Such hot-working ensures full density and a reasonable degree of chemical homogeneity.

The major disadvantage of this process, as conventionally practiced, is that a significant amount of material must be removed from the forged part to allow nondestructive inspection and to reach final shape and dimensions. The material utilization in the final part may be as low as 10 percent of the original material input.

This problem can be alleviated in one of two ways: one is to use advanced forging technology (discussed below); the other is to forge preforms, made by powder metallurgy technologies.

The preform route, which is typically used to fabricate discs, consists of filling a metal can, having approximately the shape of the final part, with alloy powder. The can is then evacuated, sealed, and subjected to hot isostatic pressing. The resulting "preform" is then forged. Use of powder metallurgy preforms may save up to 50 percent of the material.

ISOTHERMAL FORGING

In the closed-die process, the material does not flow easily into the die unless the die is preheated. Best results are obtained if the dies are at the same temperature as the forging stock. This is called isothermal forging, often referred to by the tradename "Gatorizing." Isothermal forging leads to parts that are usually inspectable by nondestructive techniques. The material savings reach 50 percent; in different terms, up to 50 percent of the input material (forging stock) is retained in the final part.

Isothermal forging has two limitations. First, the dies must consist of materials that are very strong at high temperature. If molybdenum-base products are used (ideal for this application), a non-oxidizing atmosphere is also needed. The second limitation is that only certain alloys (usually the strongest) respond effectively to this process technology.

Because control of the operation is very critical, the process is highly automated. The suggestion has been made that perhaps some of the advantages derived from isothermal forging, especially those that relate to consistency of quality, may be at least in part due to this automation rather than to the process per se. This suggestion implies that automation should be considered for other fabrication processes as well, as it may lead to better overall material utilization.

REJUVENATION OF SERVICE PARTS

As in the case of cast parts (see above), a certain degree of repair and rejuvenation is possible after service, extending life by some 10 to 20 percent.

FOREIGN COMPETITION

The United States is in the forefront in isothermal forging, hot die forging, and precision casting, although a future threat is posed by Japan.

POWDER METALLURGY TECHNOLOGIES

CONVENTIONAL POWDER

In order to apply powder metallurgy technologies, a powder must first be produced. The major process used to manufacture jet engine alloy powder is the Plasma Rotating Electrode Process (PREP), in which a bar is melted in a plasma and spun at high speed. The molten droplets freeze, usually in a spherical shape, without appreciable contamination. Of course, the powder is as clean as the starting bar.

The powder so produced can be consolidated into a bar or billet by extrusion, or consolidated into a preform by hot isostatic pressing. In both cases, the material is finally forged before being placed into service.

We found no evidence of components fabricated by powder technology alone.

Alternative technologies for the making of preforms are the Kelsey-Hays Fluid Die Process and the Universal Cyclops CAP (Consolidated by Atmospheric Pressure) Process.

The CAP process is essentially an isostatic pressing process in which the pressure is generated by the atmosphere. The powder is enclosed in a glass container and air is removed from the powder assembly. Upon heating, the glass containment softens, and the atmospheric pressure closes the porosity.

Injection molding, which is often utilized for polymer parts, has recently been considered for making preforms. In this process, a plasticizer is added to the powder, which is then injected into a hot die.

Only the HIP process is currently in an advanced stage of commercial production.

UNCONVENTIONAL POWDER

As previously mentioned, the bar stock from which powder originates may contain foreign particles that could be very deleterious. This has led to the recent development of "clean melting" technologies, which may include Electroslag Remelting, Electron Beam Remelting, and others.

Another way to avoid inclusions in the starting stock is to filter the molten metal. Ceramic filters must be used. Finally, powder may be produced in refractory-free systems.

Special powders can be produced by ultrafine particle and/or rapid solidification technologies, resulting in special cleanliness and attendant improvement in reliability and performance.

The principal advantage of ultrafine particle technology is that foreign materials, if present, are of larger size than the powder, and therefore can be physically separated. There are also advantages in the ultimate structure, homogeneity, and performance of the finished product. Above 1 micron particle size, there is no evidence that there are combustion problems with these powders. It is conceivable that below 1 micron there could be problems. It mainly depends on the type of powder and the particle size involved.

The main advantage of rapid solidification technologies is that unconventional compositions, impossible to produce by standard technologies, are feasible. Ultimately, there is an infinite latitude in the selection of alloy elements and their relative amounts. In addition, homogeneity is excellent.

While all of these unconventional technologies have tremendous long-range potential and can lead not only to conservation by major improvement in service life but also by the selection of compositions lean in critical metals, at the present time they remain in the developmental stage. Extensive, time-consuming, and expensive testing are typically needed to qualify substantial changes in materials or processing. Hence, the general assessment we obtained from ultimate users is that these unconventional powder technologies are unlikely to have major impacts on materials usage during the next decade. In no way, however, should this opinion discourage the pursuit of further advances in these very promising areas.

HOT ISOSTATIC PRESSING

Hot Isostatic Pressing (HIP), as mentioned above, is the key process that permits the use of powder metallurgy technologies. Its diffusion has been slow, because of high capital costs, high operating costs, and equipment size limitations (which also impinge on operating costs).

High operating costs are being reduced by developing equipment of larger size (thus taking advantage of economies of scale) and by developing equipment that allows rapid cooling, thus decreasing idle time. At the same time, controlled cooling can lead to improved properties.

The United States is at the forefront in HIP technology except for the size and engineering of the equipment it produces. The United States has the most HIP units in use, the largest variety of alloys being processed, and is currently leading in the basic science and engineering of how to use HIP technology most effectively. Maximum dimensions of U.S.-produced equipment extend to 60 inches in diameter. ASEA (Sweden) has a commercial 69-inch unit. This company has claimed that HIP costs can be reduced with this unit from the current range of $1.00 to $10.00 per pound to $.25 per pound.

RECYCLING AND RECLAMATION

Recycling is defined as the reuse of scrap without substantial reprocessing; reclamation is the utilization of metal values from scrap that cannot be recycled. As mentioned above, "immediate revert" is utilized in full and without time delays, and therefore cannot be considered as a "waste stream."

Several problems arise in recycling old scrap. First, it must be segregated and identified if it is to be regarded as "revert" for the production of other gas turbine parts. Second, it is often contaminated because of coatings and/or fuel and other contaminants. Finally, the supply must match the demand in kind. Currently, for instance, there is a very large amount of IN-100 scrap, for which there is no adequate demand. Specifications for alloys get modified, and hence the demand for scrap alloy changes. Also, IN-100 contains 1 percent vanadium, which makes it less easily downgradeable for many steel uses, since not many steels contain vanadium.

Whenever old scrap cannot be utilized as revert, its value can nevertheless be recovered by using it as a raw material, in, for instance, steelmaking. Here the principal difficulty is the presence of undesirable elements, notably hafnium and/or vanadium. The issue of supply and demand balance also prevails.

Some scrap, such as sludges from electro-discharge machining, cannot be recycled. Special Metals Corporation has performed research to demonstrate the preliminary feasibility of extracting the metal values by a proprietary process. (The same process would conceivably apply to miscellaneous, unsorted scrap of a different nature that is not amenable to recycling.) Major stores of sludges and other non-recyclable materials are believed to be currently available. Some of these may constitute "hazardous waste dumps." The Special Metals process could conceivably remove the environmental hazard while producing at low cost a stockpilable intermediate product. In periods of high prices or national emergencies, these intermediate products could be "finished" into a suitable feed for alloy making.

SURFACE MODIFICATION

The principal process that leads to conservation of chromium is the coating of gas turbine parts, especially rotating parts and vanes exposed to very high temperatures, with a material that retards oxidation. This material is usually an alloy containing one or two base metals, plus chromium, aluminum, and yttrium. We estimate that only a small percentage of chromium consumption takes advantage of this process, and that without its benefit the chromium content of alloys in this use would have to be increased by 50 percent. Thus, we estimate that surface modification could lead to a total savings of several thousand tons of chromium metal per year in the United States. It is unlikely that a significant advantage would derive from coating other parts that are exposed to less drastic environments.

Another process that leads to conservation of chromium and possibly of cobalt is the coating of gas turbine parts with ceramic "thermal barriers." These are typically stabilized zirconia, placed over a high-chromium intermediated layer. We believe that they are currently used only for combustion cans and probably do not lead to very substantial conservation of this metal.

Surface modification technologies could have major impacts on chromium and cobalt conservation, via surface alloying, for example.

SUPERPLASTIC FORMING/DIFFUSION BONDING

The United States is the leader in this technology, as far as titanium is concerned. The technology allows the manufacture of large complex assemblies, using a minimum of fasteners. The stock is sheet and is utilized to a greater extent than bars or plates, which must be extensively machined.

In the case of titanium, material utilization has increased by virtue of this technology from 10-20 percent to 60-85 percent. In addition, this process can manufacture turbine blades that contain only 60 to 90 percent of the material produced by forging or casting. This weight reduction, in turn, leads to further material reductions for supporting structures.

The application of this process to superalloys and the stainless steels is in the early research stages. However, not all alloys respond to it. Diffusion bonding using a HIPing technique has been demonstrated using a turbine disk powder preform (98 percent dense) and turbine blades. The HIP treatment densifies the disk and also bonds the blades to the disk by diffusion bonding. Further research will be required to assess the conservation potential of this technology.

DUAL MATERIALS

Dual materials, in which a resistant material is attached to a substrate that does not contain appreciable critical metals, have great potential for critical metals conservation.

The principal process for making dual material is cladding. Clad sheet is extensively used in the aerospace industry; the extent of its utilization in gas turbines, however, is limited to some enclosures. Another method is surface alloying, of which the tradenamed "Layerglazing" is an example. Finally, dual materials can be prepared by powder metallurgy technology.

While all these processes promise a large potential for conservation, in the case of gas turbines they do not constitute a major source of conservation at present.

SUMMARY AND CONCLUSIONS

A number of processes lead to conservation of chromium and cobalt by:

- Decreasing the amount of scrap generated during fabrication;
- Increasing the useful life of gas turbine parts;
- Improving the thermodynamic efficiency of gas turbines, thereby yielding more power per unit amount of material; and
- Reclaiming waste streams that are not now recycled.

CRA estimates that, when fully diffused, the most advanced process technologies (excluding surface modifications) that are currently commercial could save 3,000,000 pounds of chromium and 600,000 pounds of cobalt per year in the United States. These savings are for input material to the fabrication process; the net material savings after allowing for recycling would be much smaller. We further estimate that the full development and adoption of most processes now in the experimental or developmental stages could lead to an additional conservation of 3,000,000 pounds of chromium and 600,000 pounds of cobalt per year in the United States (input material). Lead times for some of these technologies are very long, possibly ten years or more. Moreover, some technologies are competitive; thus, the full development of some may obstruct the progress of others.

The general consensus is that casting technologies and isothermal forging (often in conjunction with powder metallurgy preforms) are the most promising process technologies for conservation of materials.

NON-TECHNICAL ISSUES

INSTITUTIONAL IMPEDIMENTS

Few institutional impediments were identified in our conversations with industry experts, although some respondents felt that foreign competitors enjoy tax and other incentives (as well as government support) not afforded U.S. firms.

One of the major barriers to the diffusion of new material-efficient processes is the conservatism of most designers. Such conservatism is partially caused by their educational training. For instance, many experienced designers are not versed in modern modeling approaches to process development. The number and quality of designers trained in the United States who are versed in the advanced processing of high-performance materials have also been questioned.

A barrier of a different kind is posed by Environmental Protection Agency regulations associated with the disposal of chemicals and heavy metal wastes involved in etching materials prior to visual inspection. It was stated that such regulations may increase processing costs for parts by 30 to 40 percent.*

The issues of certification and other acceptance standards were regarded as being well under control.

OIL COUNTRY TUBULAR GOODS FOR DEEP SOUR GAS WELLS

Exploitation of oil and gas deposits at very deep levels, both onshore and offshore, may claim increasing quantities of superalloys. The U.S. market for special nickel-base superalloys in this application is currently valued at about $60 million. The market is expected to reach $600 million in annual sales sometime by the late 1980s or early 1990s. These deep wells typically are 15,000 to 20,000 feet deep. At these depths, the material used in a downhole pipestring to recover the oil or gas is subjected to very high pressures, temperatures, and corrosive atmospheres. Temperatures can reach 200° or 300°C and the environment can contain hydrogen sulfide, gas, or carbon dioxide, which tends to form carbonic acid or sulfuric acid in an aqueous environment. Because of the presence of sulfur, these wells are called "sour" wells. Off the coast of Texas, there are geopressure wells where carbon dioxide-enhanced recovery is used. Here again, high pressures and temperatures exist, possibly along with some hydrogen sulfide and carbonic acid. Such drilling environments are found in the Smackover region near Jackson, Mississippi, where hydrogen sulfide concentrations are as high as 50 percent. The use of even high-strength stainless steel is precluded in these wells.

---

*A forging company direct communication.

MATERIALS SELECTION

In the traditional, shallower wells, the downhole materials have been low-carbon steels with corrosion protection provided by a chemical inhibitor that is injected down into the hole around the pipestring. Even in the deeper wells, specialty steels such as C-90, an Mn-Cr-Ni-C high-strength steel, which has some resistance to corrosive sulfide environments, are usually used. However, at the higher pressures and temperatures in the deep wells, these inhibitors break down and are no longer effective. This has caused the oil companies to seek a materials solution to the problem and to run exhaustive tests on a wide variety of corrosion-resistant alloys, from alloy steels through stainlesses and even to nickel-base superalloys, such as the following candidates:

	Composition					
Alloys	Fe	Cr	Ni	Mo	Cb	Co
Hastelloy C-276	6	16	Bal	15	--	--
Inconel 625	25	21	62	8.7	3.6	--
Incoloy 825	30	21.5	42	3	--	--
MP35N	0.3	20	35.7	9.5	00	34
MP159	9	20	26	7	0.64	35
Ferralium	Bal	26	5.5	3	--	--
Sanicro 28	Bal	27	31	3.5	--	--
Hastelloy G	20	22	Bal	6.5	2*	2.5

It is likely that these more expensive high alloy materials will not be used for an entire pipestring but as hole liners in the most corrosive areas at the bottom of the string. The liner in this case would protect a high-strength alloy steel like 2.25 Cr-1Mo, which would form the main body of the string. An alloy such as Hastelloy G or Inconel 325 might be used for the middle part of the string.

---

*Cb+Ta

In 1980, 743 deep gas wells were drilled; in 1981, 900 wells were drilled. Only about 1 to 3 wells during this period were deep sour gas wells, but this total might eventually increase 10 to 20 wells per year. Of this total, possibly only two wells per year would require a high alloy material like Hastelloy C-276 in the pipestring. Undoubtedly, an increasing number of wells will require these alloys, but only recently have high-alloy materials been used in deep sour wells, and most of the above-mentioned that were drilled in 1980 and 1981 did not use high alloy in the pipestring.

The tonnage of all corrosion-resistant alloys being utilized today in the deep sour wells is estimated at 3,000 tons per year, broken down by alloy types as follows:

Low Alloy (13% Cr type)	2,000 tons
High Alloy (20-30% Cr; 25% Ni)	1,000 tons

The pipestrings can vary in weight from approximately 6 pounds per foot of length to 30 pounds per foot of length. This translates into 50 to 225 tons of total material required per 15,000-foot string. Therefore, in deep sour gas wells there could be a maximum of 450,000 to 500,000 pounds of high-performance alloy required per well. In the typical well, however, the amount of high-performance alloy will probably be limited to the lower sections of the pipestring, and the exact dimensions will vary according to the nature of the corrosiveness and temperature in the well. A few thousand feet of corrosion-resistant tubing might be required in a very corrosive deep well.

Hastelloy C-276 has been used in two wells in Mississippi, with thousands of feet of conventional seamless tubing involved. Due to the wide-ranging environments in the deep oil and gas wells, not all wells will require high chromium and nickel superalloy type materials for downhole pipestring applications. Such candidate alloys as Hastelloy C-276, Ferralium (3.5% Mo), or Sanicro (3.5% Mo) will likely only be used in limited quantities, either for liners or for full sections of a string in severely corrosive wells. As long as corrosion damage has not occurred to a pipe string, it may be reused, depending on the well type.

One of the major materials developments that could greatly influence critical metals usage is the use of clad steels, whereby a clad layer of a nickel-base superalloy is bonded to a backing of plain carbon or alloy steel. The cladding itself represents a savings of 80 to 90 percent of highly-alloyed material, and at least 50 percent in costs in comparison to using a solid high alloy pipestring. However, the economics in favor of using a clad product change with the diameter of piping specified. Smaller-diameter pipe has less material costs relative to fabricating cost, so a clad pipe loses its advantage since clad primarily reduces expensive alloy usage. At larger diameters, materials costs become relatively more important and clad products can then be more cost-effective. For pipe sizes that are greater than about three inches in diameter, the economics favor a clad product.

A problem with clad products is the potential for separation of the cladding from the base. In addition, since the cladding is usually produced by bonding one sheet onto another, the ends of the base metal are still unclad and exposed. These two factors are important in downhole applications because if any base metal becomes exposed by separation or an unclad surface, the pipe will corrode and fail rapidly. Clad products also demand careful handling so as not to damage the cladding, which would necessarily increase the cost of the product. So far, the economics only favor claddings consisting of high-nickel alloys or highly-alloyed ferrous alloys and not the standard stainless alloys like Types 304 or 316.

The oil industry in the United States has traditionally only used seamless pipe because welded pipe has often failed at the weld joints. Currently, there is a limitation in the United States on the availability of larger-diameter seamless pipe that could be used for an oil country clad product, but new mill capacity has been announced by several U.S. steel companies. A few steel companies have been producing clad steel plate for some time now. The plate products can be further formed into tubular products, but these would be welded. One company, Lukens Steel, offers a large range of claddings, from pure nickel and nickel-base superalloys like the Inconels to stainless steels and the cupro-nickels on plate products. The Japanese also offer very good cladding technology, particularly for large-diameter superalloy clad tubulars for the oil industry. They recently supplied 10-inch pipe clad with a highly-alloyed duplex stainless steel for a Saudi Arabian project, having developed a product significantly cheaper than solid high-nickel alloy pipe.

In the future, clad tubing use in the oil country industry should increase, as improved quality and suitable new products become available. Clad tubing will find use in selected deep wells, where it provides good, cost-effective performance, reducing costs by 50 percent on average over the solid high-alloy goods and reducing critical metals requirements per pound of pipe by 80 to 90 percent. In other more demanding situations, solid high-alloy pipe will be specified for reliability and performance.

STEEL PLATE IN HEAVY EQUIPMENT AND CONSTRUCTION

Steel plate is a common construction product that is produced in varying lengths, widths, and thicknesses in many types of alloy compositions, from plain carbon steel to alloy steel and stainless steel. By far the largest tonnage of steel plate is in the plain carbon steel category. The American Iron and Steel Institute reported* that total raw steel production in the United States amounted to 120.8 million net tons in 1981. Of this, 101.5 million net tons was carbon steel, 17.6 million net tons was alloy steel, and 1.7 million net tons was stainless steel.

The primary alloying element of concern in this category is manganese, with a secondary emphasis on chromium in the alloy steel products. Technology changes in steelmaking and primary product fabrication will influence the future use of manganese.

---

*AISI Annual Statistical Report, Washington, D.C., 1981.

The amount of primary manganese added in steelmaking includes both ore additions to the blast furnace and manganese ferroalloys used during steelmaking (in the BOF or electric furnace). The three main steel categories have different averge manganese contents. Carbon steels are divided into two categories: low-carbon, flat-rolled products containing an average of 0.35 percent Mn (comprising two-thirds of total shipments) and the remainder containing 1.0 percent Mn. For all carbon steels, the average content is about 0.6 percent Mn.

The manganese content of alloy steels varies widely, from 0.35 percent to 1.8 percent, with an average of about 0.9 percent. Electric furnaces using all-scrap charges produce about half of all the alloy steel. In stainless steel the average manganese content is 1.7 percent.

Processing developments that will influence the use of manganese are occurring in the areas of:

- Ironmaking -- the production of raw iron for steelmaking;
- External desulfurization of blast furnace hot metal and other pretreatments;
- Primary steelmaking;
- Ladle refining;
- Continuous casting; and
- Forming.

Ironmaking involves the production of raw pig iron from iron ore and other constituents such as coke and limestone. The trend has been continuing to shut down the older, less-efficient blast furnaces in favor of the newer furnaces with improved productivity. Better procedures for charging and tapping the furnace, relining, and furnace control technology have led to reduced fuel and energy requirements per ton of hot metal produced, and have improved the efficiency of utilization of raw materials in the furnace. However, these trends alone are not expected to alter manganese utilization. Manganese utilization in ironmaking depends greatly upon the kinds of raw materials fed into the blast furnace, which determine the chemistry of the hot metal produced. While there are wide variations, most pig irons contain 0.6 to 0.8 percent Mn.

Manganese ore is popularly supposed to be added to the blast furnace to improve desulfurization, but it is likely that it simply provides a cheaper source of manganese than ferroallboys added in steelmaking. Additionally, it improves slag formation in steelmaking by the basic oxygen process, where it substitutes, to some extent, for fluorspar. Its effect on desulfurization in the blast furnace is due to its action as a deoxidizer, but for this purpose silicon is more effective, though less desirable in the subsequent steelmaking process. Charging of manganese ore, however, is an economical way of adding manganese to steel because about 75 percent of the manganese added as ore is retained in the pig iron. Downstream, about 75 to 80 percent of the ferromanganese added to the steel furnace charge is lost to the slag by oxidation.

It should be emphasized that manganese ore is by no means the only manganese input to the blast furnace; other sources include iron ore and recycled steelmaking slag. However, the cost of adding manganese as ore to the blast furnace is much lower than the cost of ferromanganese added in steelmaking.

The increasing practice of external desulfurization of hot metal after the blast furnace production in torpedo cars or ladles is expected to relax some of the requirements for desulfurization in the blast furnace, specifically reducing the use of basic slags for desulfurizing in favor of more acid burdens (less lime, more silica). This practice would decrease the manganese recovery in the hot metal below its usual average of about 75 percent. To compensate, manganese ore additions might be implemented, which, at about $1.40 per ton of ore, would not be expensive. The resulting higher manganese oxide content of the slag during steelmaking (in the basic oxygen furnace) would require less fluorspar (required for good slag properties). The cost of fluorspar is over $90 per ton, and savings in fluorspar are expected to offset increasing the manganese content of pig iron.

An alternative procedure is to increase the recycling of steel furnace slag, a practice already implemented by most operators. Steelmaking slags grade about 5 percent manganese oxide, 15 percent iron oxide, and 45 percent calcium oxide. Such slags are very low-grade sources of manganese, but important sources of iron and calcium (to replace limestone flux additions) in blast furnaces. The extent to which slag can be recycled is limited by the building up of phosphorus and residual elements such as chromium. Practiced to its full extent, slag recycling would permit manganese savings, as alloy, of up to 0.5 pounds per short ton of steel. The driving force for significant increases in slag recycling is likely to come only if manganese prices increase dramatically.

The declining quality of ironmaking raw materials, such as lower-grade iron ores (with lower associated manganese and higher residual contents) and higher-sulfur cokes, results in larger amounts of blast furnace slag. This translates into lower residual manganese contents in the hot metal and requires increased manganese input. If silicon and phosphorus contents can be minimized, the quantity of slag can be kept low and will require less added manganese as more expensive ferroalloys later in the steelmaking process. Because of differing steelmaking practices in different plants, it is difficult to define the tradeoffs quantitatively for the industry, but more expensive ferromanganese in the BOF can be replaced by cheaper manganese ore in the blast furnace to attain required manganese specifications.

EXTERNAL DESULFURIZATION

Although a number of methods are available for ladle treatment of molten pig iron, it is likely that injection of calcium carbide or magnesium metal will, in the long run, be the preferred technique. External desulfurization will eventually become a desirable practice if higher-sulfur coking coals are permitted. An illustration of this is provided in a recently-published study on the economic benefits of external desulfurization.* The study found that for a typical steelmaking practice (statistically averaged operating parameters across a large number of plants), the operating cost savings were $4.00 per net ton hot metal, assuming no change in specifications of raw materials or steel products. In addition, blast furnace productivity was increased by 7.7 percent, and potential capital cost savings in blast furnace and coke plant capacity required were calculated at $9.85 per net ton capacity. Required manganese content in the steel was reduced on average from 0.8 percent without desulfurization to 0.7 percent with desulfurization, a reduction of 12 percent. Reduction of the sulfur content of pig iron from 0.035 percent (readily attainable now) to 0.015 percent by external desulfurization is quite feasible; in fact, reductions to lower levels have been demonstrated.

Given the conservative nature of the steel industry, it is unlikely that the manganese content of those products that use manganese primarily for sulfur control would drop below 0.2 percent. Since other measures for saving manganese considered here are expected to have been instituted before external desulfurization, the manganese content is assumed to drop from 0.35 to 0.2 percent, for a possible long-run saving of 3 pounds per short ton. Such a saving, however, would be applicable only to a portion of the carbon steel production. Of total carbon steel production, about half is flat-rolled (excluding plate), but it is estimated that only about 70 percent of this production requires manganese primarily for sulfur control. The savings are therefore estimated at 35 percent of 3 pounds, or 1 pound per ton, of carbon steel production.

LOWERING THE MANGANESE-TO-SULFUR RATIO

The principal function of manganese in carbon steels that are not heat-treatable is to control sulfur. Without manganese, sulfur in steel precipitates as iron sulfide at grain boundaries during solidification. The melting point of iron sulfide is low enough that the precipitate is liquid at forging and rolling temperatures, leading to "hot-shortness." Manganese, which has a stronger affinity for sulfur, increases the melting point of sulfide precipitates sufficiently to prevent this phenomenon. It is generally believed that a manganese-to-sulfur ratio of 10 is sufficient to make the sulfides predominantly MnS. Manganese specifications, however, were written for maximum sulfur contents of 0.05 percent. Improvements in modern blast furnace practice have made possible carbon steels with sulfur contents no higher than 0.035 percent, so that, in most cases, the manganese-to-sulfur ratio is between 15 and 20.

---

*J. C. Agarwal et al., "Economic Benefits of Hot Metal Desulfurization to the Iron and Steelmaking Processes," ISS-AIME BOF and Open Hearth Conference, Toronto, March 1981.

With respect to the possible savings to be realized through a reduction of this ratio, it must be borne in mind that the use of manganese for sulfur control is the principal use for only a certain percentage of carbon and alloy steels. For the rest (largely the flat-rolled products), manganese is also an alloying element for ferrite strengthening or for increasing hardenability.

Taking into account all the factors involved, manganese savings that are possible by reverting to a manganese-to-sulfur ratio of 10 are estimated to range from 0.5 pounds per short ton in the short run to 2.5 in the long run. The latter figure implies lowering the average manganese percentage in carbon steels by 0.13 percentage points and would necessitate some new specifications. A complicating factor is the expected sulfur content of steel for different geographical areas, depending, for example, on the availability of low-sulfur coking coals. There are no obvious cost penalties associated with these changes, but market inertia may be important.

PRIMARY STEELMAKING

In the basic oxygen processes, the increasing use of bottom-blowing and inert gas mixing techniques is resulting in greater recovery of manganese. Current recoveries average between 30 to 50 percent in the BPO (the higher the final carbon content and temperature, the higher the manganese recovery). Manganese recovery should therefore improve to 40 to 60 percent over the 1980s as these practices become more pervasive. In addition, the use of open-hearth furnaces, which have the highest unit consumption of manganese of all the processes, is gradually being phased out, which will contribute to lower manganese consumption in steelmaking.

Another important trend is the increasing steel tonnage being produced in the electric furnace. Manganese recoveries are higher in electric furnaces because there is a higher proportion of scrap in the charge. In addition, as the furnace operates mainly under reducing conditions, the quantity of slag is reduced, thus increasing manganese recoveries in the steel. It is also important to realize that measures taking effect through changes in blast furnace practice will not affect carbon steel produced in electric furnaces (because of the small amount of hot metal used).

Thus, for the reasons mentioned above, the electric furnace practice uses less ferromanganese. The difference between the basic oxygen process and the electric furnace process (to the extent that the charge for the latter is close to 100 percent scrap) will disappear if the manganese content of pig iron increases. For this reason, the increasing percentage of steel made in electric furnaces may not ultimately affect unit manganese consumption, provided that all-scrap changes are the norm. It is more likely, however, that there will be an increasing usage of direct-reduced iron pellets in electric furnaces. Such pellets are low in manganese, so overall manganese addition requirements may increase as more electric furnace capacity is introduced. This effect should offset almost entirely any reduction in manganese consumption resulting from the phasing out of remaining open-hearth production capacity.

LADLE AND SECONDARY REFINING

The use of ladle and secondary refining has grown rapidly during the 1970s and 1980s. An example is the growth of the AOD process, which has brought much greater control to stainless and specialty steelmaking. The argon gas atmosphere protects the melt from excess oxidation during processing as well as in subsequent pouring, thereby reducing the loss of manganese. Again, desulfurization in the ladle reduces the need for manganese to control sulfur in the steel. The use of silicomanganese as a manganese additive in place of high-carbon ferromanganese is also attractive because of the superior deoxidizing properties of silicon, and such use would result in some savings in manganese.

CONTINUOUS CASTING

The current amount of steel continuously cast in the United States is about 28 percent. This is expected to increase over the decade. The share should approach 50 percent by the mid-1980s and potentially 70 percent by the year 2000. Continuous casting results in higher product yields from molten steel (+10 percent), better quality, lower energy requirements, lower metal losses from scaling on ingot reheating, and reduced losses due to less scrap recycling. These factors tend to lower the overall manganese requirement by lowering the raw steel requirement for making products. In some products, such as billets and blooms, slightly-increased manganese levels are preferable in continuous casting to avoid hot cracking in the first cooling stage (beyond the mold).

CONCLUSION

Manganese savings achieved through technological advances in steelmaking and fabrication will vary for the different steel categories. The greatest percentage savings will occur with carbon steel production, primarily because there is greater flexibility in the final manganese specifications in the steel. In alloy steels, manganese is an alloying element specifically used to strengthen ferrite and increase hardenability; its use cannot be reduced very much. Also, since about 40 percent of U.S. alloy steel production is in electric furnaces, the potential savings are lower than for carbon steel. For stainless steels, only minimal savings appear possible.

There will be a tendency to trade off increases in manganese input to the blast furnace, which are relatively inexpensive, with reductions in downstream additions of ferromanganese, which are more costly. This is partly brought about by increased use of high-sulfur coke and the use of ores higher in residuals like phosphorus.

The potential savings in manganese use resulting from the various technical developments described above are summarized below:

	Savings in Ferroalloy per Ton Steel
External hot metal desulfurization	1 lb Mn
Continuous casting	Minimal unit savings
Change in furnace types:	
Electric furnace vs. open hearth	nil
Blast furnace practice changes (ore additions)	1 lb Mn
Slag recycling	0.5 lb Mn
Lowering Mn/S ratio	(short run) 0.5 lb Mn (long run) 2.5 lb Mn
Silicomanganese in place of ferromanganese (for higher manganese prices)	0.8 lb Mn
Total	(short run) ≥ 3.8 lb Mn (long run) ≥ 5.8 lb Mn

These reductions or increases in manganese use are based on an average manganese content, as ferroalloys in carbon steel, of 12.7 lbs Mn, in alloy steel of 20.4 lbs Mn, and in stainless steel of 19.8 lbs Mn, for an average of 13.8 lbs Mn over all types of steel. The short-run savings (i.e., through the 1980s) may amount to 30 percent, while the long-run savings beyond 2000 may reach at least 40 percent of present consumption of manganese in ferroalloys and metal.

SUMMARY AND CONCLUSIONS

This chapter has provided an overview of new processing technology as applied to three specific end use areas. The new technologies will continue to be applied to more end uses than can be discussed here. The state-of-the-art today in jet engine part fabrication will eventually filter down to lower technology applications, such as in parts used for chemical processing and automotive or off-highway vehicles, to name but two.

Superalloy usage is spreading to non-aerospace uses, such as oil country tubular goods, military equipment, heavy duty tooling, waste incineration, glass manufacture, heat recuperators, auto/diesel engine parts, flue gas desulfurization, marine hardware, pulp and paper production, medical and dental applications, and nuclear processing. The new technologies are likely to diffuse into these end uses as performance and cost-effectiveness continue to be emphasized.

Powder metallurgy technology is currently being applied to the production of tool steels in order to make more homogeneous structures with enhanced, more uniform properties. HIPing is being applied to sintered carbides to increase the service life of cutting tools and drill bits by up to 50 percent. HIPing is also being used for hardfacing oil pump liners and oil well hardware; for locomotive drive wheels, pumps, and valves; and in areas where composite (two-layer) metals will be feasible, such as in composite forging dies and prosthetic implants.

Superplastic-forming and diffusion-bonding are broadening their applicability from aerospace uses. They are being applied to turbo pump casings and chemical processing plant applications. Large precision castings are likely to be implemented in automotive and off-highway vehicle applications in the future.

Automation will continue to be emphasized, along with computerized sensing and control, to increase throughput rates and precision of parts, which will translate into higher yields and efficiency at lower costs. Nondestructive testing is becoming more computerized and will eventually be capable of quality-testing net shape parts.

In gas turbine engines, cobalt and chromium savings as a result of process advancements should amount to 10 to 12 percent of current usage by the late 1980s. Chromium use in oil country goods is expanding at present. The future market for high performance oil country tubular goods could represent a $600 million market by the late 1980s. Cladding of plain steel with superalloys for the same corrosion-resistance as solid products could limit the growth in demand for chromium, since claddings would use only 10 or 20 percent of the chromium. Finally, process changes in basic steelmaking and fabrication are expected to reduce future requirements for manganese, particularly in the control of sulfur. A savings of 30 percent in ferroalloy is conceivable in the 1980s, with 40 percent possible in the 1990s.

4

TECHNICAL, ECONOMIC, AND INSTITUTIONAL FACTORS

This chapter will cover the technical and nontechnical factors hindering further growth of the various fabrication technologies. The discussion will include technical barriers to advances in utilization of near net shape technologies, directions of ongoing research and development efforts, the potential impacts of new technologies, and institutional barriers.

TECHNICAL BARRIERS

There are many technical problems that still must be solved to advance the state of the art. It is felt by most sources that these will be overcome by evolutionary rather than revolutionary advances. Even without any new technologies, there are many interesting metals-forming and fabricating techniques, introduced commercially only in the past few years, that still have much future potential to be realized.

Before discussing such specific areas as forging technology, casting technology, and surface modification, we note a number of important technical barriers that apply across many of the technologies, including:

- Obtaining clean metal. This is primarily of concern in making superalloys by melters, casters, forgers and users alike. There is much R&D being conducted on advanced melting and refining techniques such as vacuum induction melting, vacuum arc remelting, electroslag remelting, and electron beam melting to lower impurity contents. Makers of jet engines would like to double the service life of forgings (conventional and isothermal) using superclean metal.

- Lack of suitable and cost-effective refining processes for recycling. Some scrap superalloy material is being recycled. The goal is to be able to take scrap (such as machining chips) and reprocess it back into alloy that can go directly into the high-performance parts of a jet engine rather than be downgraded for some other less-demanding use or as a steelmaking additive. In addition, cost-effective processes must be developed to recover metal values from dusts and the so-called ECM sludges, which are typically low-grade materials that are difficult to handle.

- Inadequate inspection methods for finished parts. Ways of circumventing the limitations of acid inspection techniques are needed. Acid handling and disposal are major problems and have become very costly under existing EPA regulations dealing with wastes containing heavy metals. However, acid inspection appears to be the only effective way at present to check the integrity of a large billet cross section for cracks, inclusions, grain structure etc. Nondestructive evaluation methods based on computer-controlled sonic inspection (using sound wave transmission) are increasingly being used, but they lose their sensitivity when inspecting large billet sizes where acid inspection is most effective.

Another important area that applies to forging, casting, and powder techniques is increased automation of processes. The driving forces are, of course, increased productivity and reduced costs. Some of these technologies such as hot die forging, precision casting of intricate shapes, and HIPing, are not highly automated. Technology will have to be developed to reduce labor intensiveness and improve controls in order to increase the degree of automation and make these processes more cost-effective.

FORGING TECHNOLOGY

One of the major technical problems in forging to net shape lies in the inspection process. Current ultrasonic techniques used to inspect turbine forgings can only give reliable results up to a certain distance from the surface. If, for example, an ultrasonic system can see a defect no closer to the surface than 0.100 inch, inspection must then be performed on a surface at least 0.100 inch from the finished part surface to ensure that defects in this uninspectable zone are outside the finished machined product. The minimum shape that can be currently forged is the sonic shape (illustrated in Figure 2-17). If the inspection technique were more sophisticated, forging could be performed possibly to 0.05-0.06-inch accuracy or even net shape. Work is being conducted on "smart" sonic inspection technology that does not require a flat surface to inspect and that also narrows the sonic envelope closer to net shape. The Air Force Materials Laboratory, DARPA*, the Rockwell

---

*Defense Advanced Research Projects Agency.

International Center for Advanced NDE, and the major jet engine manufacturers are all active in this area.

Other technical problems relate to improving the forging die, both through die design and better die materials. The dies must be able to maintain their integrity at high operating temperatures. Therefore, they are made from sophisticated and expensive high-performance nickel-base alloys and molybdenum alloys like TZM. With the exception of TZM, dies of these alloys are very difficult to machine; they must have a long operating life and be oxidation-resistant. The main die material for precision forging of nickel-base alloys is TZM, which must be used in an inert atmosphere to avoid rapid oxidization at high temperature. This adds to the difficulty and expense of forging. The dies are also non-weldable, which creates problems with die repair and making die changes. There is at present little R&D being conducted for new molybdenum-base alloys. There is a need for a cheaper die alloy that needs no inert atmosphere, since molybdenum rapidly oxidizes in air when heated.

The die lubricants also need more improvement. Production-run sizes are currently limited because of the tendency of state-of-the-art lubricants (e.g., boron nitride and glass frit-based types) to build up in the die cavity. As better lubricants are developed, greater control can be exercised on the process, with improvements in productivity and increased net shape capability.

Advances in casting technology will be necessary to permit the high-quality casting of larger die blocks with a significant amount of impression for larger parts. This capability plus advances in die design (assisted by CAD/CAM technology) permit the production of larger forgings by near net shape techniques than are possible today.

Isothermal forging is now a fully-automated process that uses either powder preforms, extrusions, or conventional forging stock as input material. Hot die forging is less automated but work is going on to make it as automated as isothermal forging. These forging technologies have enabled hitherto unforgeable high-strength alloys like IN-100 (10% Cr-15% Co), MERL 76 (12% Cr-19% Co), RENE 95 (14% Cr-8% Co), and, to a limited extent, Astroloy (15% Cr-17% Co) to be forged into components that have optimized the properties available in these alloys for the most stringent areas of the jet engine. Other important alloys like IN-718 are not die-forged.

PRECISION CASTING

The major challenge in precision casting is to increase the size of such castings. Casting is an advantageous process for near net shape parts in certain complex shapes that involve joining, such as in disk and blade assemblies.

At the present time, the leading company in the field is Precision Cast Parts in California, which specializes in large castings. The firm has produced parts up to 500 pounds each. Eventually, it is expected that entire sections of engines will be integrally cast.

In casting, as in forging, it is important to reduce the amount of machining and approximate net shape as closely as possible. For turbine buckets there is some machining of the attachment but 90 to 95 percent of the usable casting is fly weight. Most of the scrap generated is "immediate revert" and can be recycled without further processing. There is also work being done to improve control of "old scrap," so that pedigreed retired parts can be returned to their origin and be recycled.

In casting small parts such as turbine buckets, the buy-to-fly ratio from casting to finished part is about 1.2 to 1, versus 5 or 6 to 1 commonly seen in conventional forging and casting. There is a drive to achieve this same ratio with larger parts to reduce final machining costs.

In the directional solidification of turbine blades for the wafer blade concept (whereby two halves of the blade are cast and then diffusion-bonded, leaving a hollow core which enables air cooling of the blade), the primary problem is for better nondestructive testing for microscopic flaws of one micron or less in size within the diffusion bond.

Another current technical limitation applies both to superalloys and to stainless and alloy steels. There is a need to develop accurate design data for smaller, lightweight castings. Fatigue and fracture-toughness data are being developed to improve metal utilization and cost-competitiveness of castings. Some of this work is being organized by the Steel Founders Society of America. The SFSA research is beginning to generate guidelines for castings for low-temperature applications, as in Arctic pipelines.

POWDER METALLURGY

The major advances at present in powder metallurgy relate to enhancement of powder quality to avoid foreign impurities, improvements to and further penetration of hot isostatic pressing for near net shape and net shape components, attainment of better reproducibility of parts production, and realization of the potential benefits offered by rapid solidification technology.

There has been an ongoing drive toward better control of powder quality. One approach is to produce superfine (325 mesh) powders to screen out impurities. Superfine powders will produce a fine-grained ingot and fewer crack initiators, but the powder costs of $25 to $30 per pound make this an expensive alternative. Superfine powders are likely to be used only when there are special parts with design restrictions.

In HIPing, the main problems have centered around reproducibility and have been especially related to input powder quality. HIPing is recovering from the bad name it received with General Electric's efforts to HIP RENE 95 alloy powder components that had low cycle fatigue failures in service. The powder defects have more recently been minimized, but there are still problems in achieving close, reproducible tolerances with HIP.

The scale-up of the HIPing process to produce larger parts is a major technical problem and equipment improvements are needed. In addition, the cooling rate after HIPing should be faster for improved productivity. Development work is continuing in both these areas in the United States and abroad. The HIPing process today is a batch-oriented and labor-intensive operation and further automation of the process would improve its cost competitiveness with other processes. The capital costs of HIPing equipment are also quite high, making the process prohibitively expensive for many kinds of parts, and slowing its expansion in use.

In the use of HIPed castings, which are presently implemented on a limited scale, some fabricators point out that corrective heat treatments are needed after pore healing by HIP, which adds to the cost of the part. There is also the question of whether the optimum morphology can be reproducibly obtained in the microstructure of the part.

With respect to the mechanically alloyed materials like MA754 and MA6000E, the fabricators tend to favor clean metal, asserting that melters are going to such great lengths to remove impurities like oxides and nitrides that paying more to have them reintroduced in an ODS alloy is senseless.

In rapid solidification technology there are many unsolved questions and a great deal of fundamental property data are still needed. One of the major problems is the high cost and limited availability of RST powder. One fabricator indicated it will require 5 to 10 more years for enough RST material to be produced for commercial operations. So far, the main commercial RST activity has been in aluminum. There are also problems caused by the effects of subsequent compaction and heat treatment, which can drastically alter the original rapidly-cooled morphology and properties. One solution worth exploring is the explosive compaction process described in Chapter 2.

Major constraints on RST utilization are costly vacuum handling of powders; potential introduction of nonmetallic inclusions and contained porosity; grain boundary migration impedance that is not well understood; and the theoretical base for nucleation and growth, phase equilibria, and heat transfer in these alloys, which is only partly developed.

SURFACE MODIFICATION, COATINGS, AND CLADDING

With the exception of ion implantation, most of the surface coating processes (described in Chapter 2) are commercially practiced. There are few technical barriers to them, and major developments primarily aim at the improvement of their process economics.

Ion implantation is unique in many respects and has major potential. The principal technical barrier is the development of commercial high-ion density implantation equipment. The cost of such equipment is prohibitively high at the present time.

Surface modification processes have served well, but in new applications there is often reluctance to adopt them in favor of using solid alloys that perform satisfactorily. The principal concern is the presence of flaws, either in the as-processed condition, or caused by handling or service conditions. These flaws could lead to sudden and often catastrophic failures. Another concern is the joining of surface-modified workpieces. For these reasons, the assessment of these processes for conservation of critical metals can be done only on a case-by-case basis.

Many types of coatings are not self-healing. If a nick in the coating occurs, the base metal will be exposed and corrosion will inevitably set in (galvanizing is one traditional coating that is in fact self-healing). Coatings are often very hard and brittle even though they have the proper corrosion-resistance. Some types of coatings will alloy with the matrix, rather than remain as a distinct surface layer. This dilution effect is more difficult to control with coating processes like gas-tungsten spraying and plasma spraying, where dilution can reach 5 to 15 percent. In laser cladding, dilution is quite low at under 2 percent, because of the rapid solidification of the thin melted layer at the surface. In hard facing, however, dilution can be as much as 20 to 50 percent.

In claddings, which are typically thicker than coatings, one of the main problems is the difficulty of welding. Clad products are also very vulnerable to handling damage. Claddings can unbond and separate away from the base metal, which will cause catastrophic failure in severe conditions. Key companies involved with cladding are Lukens Steel and Phoenix Steel, which deal with hot-bonded heavy gauge, and Texas Instruments, which deals only with thin gauges.

SCRAP RECYCLING

Until recently much of superalloy scrap was not being recycled because the technology had not been sufficiently developed to enable adequate reprocessing, even if the material were segregated by alloy type. However, large quantities of machining chips could be processed using electron beam melting or electroslag remelting. The resulting alloy could be used again in high-performance engine parts and not be downgraded for lower-performance parts. The major cost item today lies in segregating the scrap by alloy type to avoid elements such as hafnium and yttrium, which are only useful in specific types of alloys and could be detrimental in other applications.

The recycling of ECM and EDM sludges and flue dusts was previously believed to be impossible on the basis of their low grade and, therefore, potentially high cost of recovery. However, some companies have developed solvent extraction processes for recovering metals from the sludges. If the high cost of disposing of these sludges is considered, these new recovery processes are economical, but apparently no government money is being made available to assist in the pilot plant and process scale-up activities prerequisite to making these processes commercial.

The reclamation process from sludges can be stopped at a point where the product (like a concentrate) is environmentally safe and can be stockpiled in intermediate form. The process can be completed later when high demand develops.

ECONOMIC BENEFITS OF NEW PROCESSING TECHNOLOGIES

Most of the new technologies are being used with high-performance materials from which very expensive parts are made. The material input costs are such that it pays to use new and indeed relatively expensive technology that can, in the end, reduce overall production costs. Such is the case with new near net shape forging and casting technologies.

Diffusion of the new technologies to lower-cost materials will take some time and will result in better quality forgings and castings. However, the gains from using new technology are not compelling if the materials cost is less than $5.00 per pound. Advanced fabrication techniques are currently applied primarily to the superalloys, the specialty steels, and titanium alloys, particularly for aircraft and aerospace uses. As shown in Table 4-1, the material and processing costs to produce chips are very high for jet engine components and represent an enormous area for cost reduction possibilities. The reduction of machining costs in near net shape technology often constitutes the major cost reduction element.

FORGING

For isothermal forging, Figure 4-1 illustrates the cost reduction possibilities of the near net shape process. The original compressor disk for the F-100 development engine was machined from a 250-pound Astroloy forging. The current disk is machined from a 126-pound IN 100 isothermal forging to make the 15-pound finished part. About one-half the input material resulted in one-half the generated scrap.

Table 4-1

ENGINE BUY/FLY MATERIAL BREAKDOWN FOR PRATT AND WHITNEY JT9D JET ENGINE

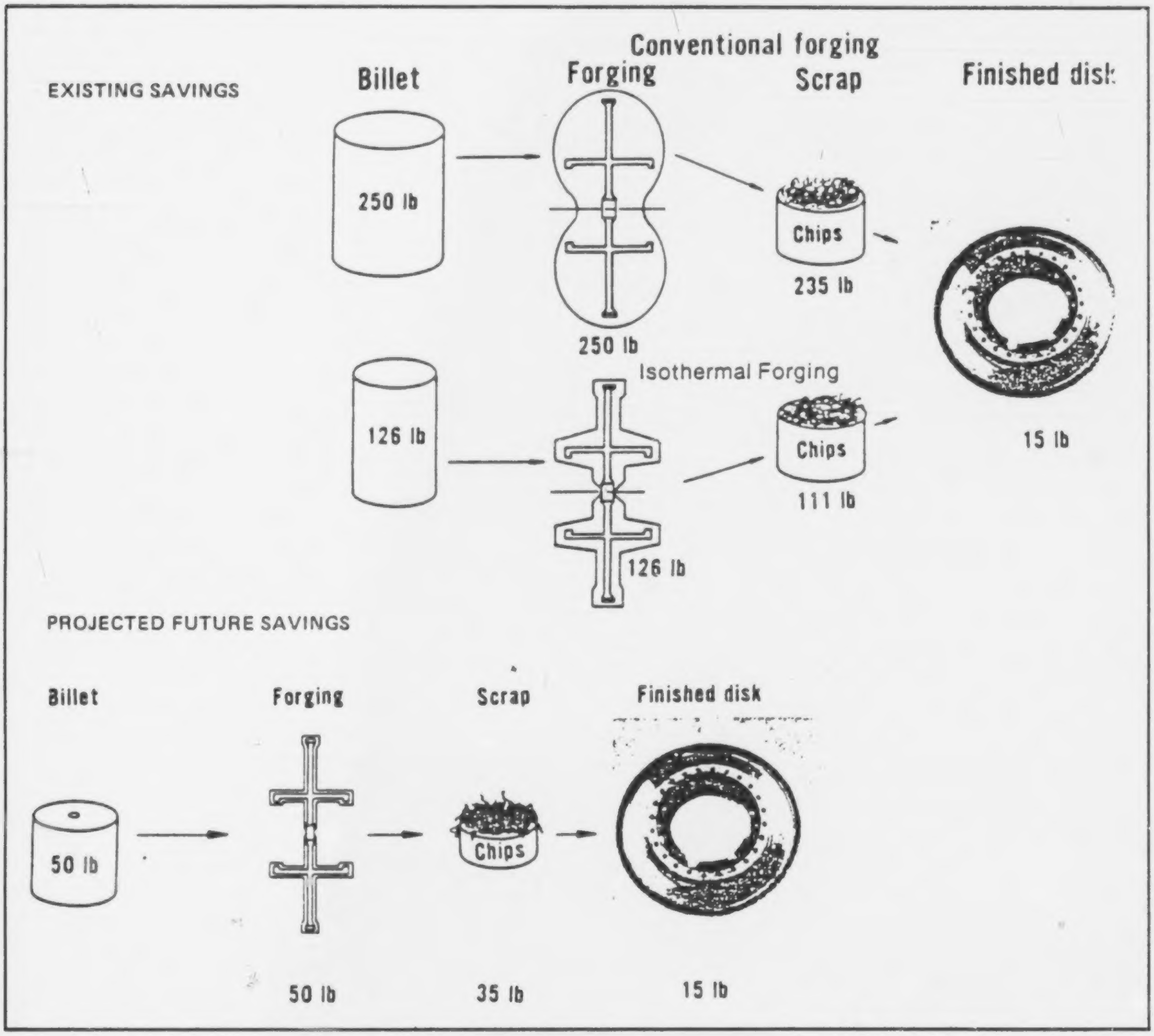
	Buy 103 lb	Fly 103 lb	Chips 103 lb	Material Cost Fly	Material Cost Chips	Rough Machining Cost
Aluminum	2.407	0.584	1.823	$ 982	$ 3,080	$ 2,930
Stainless Steel	14.498	1.537	12.961	$ 1,960	$ 16,480	$ 44,500
Titanium	11.718	2.055	9.663	$ 9,800	$ 46,200	$ 89,700
Nickel	17.811	2.966	14.845	$ 17,000	$ 85,500	$ 156,000
				$ 29,742	$ 151,260	$ 293,130

NOTE: Buy/fly ratio = ratio of the weight (or cost) of raw material that must be purchased for a given part or product to the weight (or cost) of the finished part or product itself.

SOURCE: Isothermal and Hot-Die Forging of High-Temperature Alloys, MCIC-83-47, June 1983, Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio.

Figure 4–1

ISOTHERMAL FORGING IMPROVEMENTS OVER CONVENTIONAL FORGINGS


EXISTING SAVINGS
Conventional forging
Billet
Forging
Scrap
Finished disk
250 lb
Chips
235 lb
250 lb
Isothermal Forging
126 lb
Chips
111 lb
126 lb
15 lb
PROJECTED FUTURE SAVINGS
Billet
Forging
Scrap
Finished disk
50 lb
Chips
50 lb
35 lb
15 lb

SOURCE: *Production to Near Net Shape Source Book.* 1983. American Society for Metals. p. 110.

The major costs for forging are from:

(a) die material;

(b) die machining and die set installation (labor);

(c) workpiece material and lubricants;

(d) preheating and forging operations (labor and energy); and

(e) rough and finished machining of forgings (labor).

The materials for isothermal and hot die forging are much more expensive and difficult to machine than die steels for conventional forging. However, near net shape forging involves fewer forging stages (item d), which reduces the significance of high die costs. The die costs and set-up costs are therefore high and the run sizes are small; the forging input material and costs are, however, low and machining costs are also low with isothermal and hot die forging. Cost savings in the manufacture of turbine disks from nickel-base superalloys have been quoted as high as 46 percent over conventional forgings. Further experience is expected to increase these savings. Figure 4-1 shows the possible future gains in isothermal forging. The forging is down to 50 pounds in weight, with an additional saving of 76 pounds of chips.

A comparison of hot die forging with the conventional forging of two titanium alloy parts (similar economics as with superalloys) was performed at Wyman Gordon.* For a connecting link of 38.3 pounds conventional forging weight and 29.0 pounds hot die forging weight, a run size of about 170 parts was necessary for the hot die forging to be cost-effective. For the other part, a bearing support, the figures are 122.0 pounds conventional and 46.5 pounds hot die, with a run of at least 460 parts for the hot die forging to be cost-effective. The breakeven points for these two dissimilarly-shaped parts are different, indicating that a complex interaction of differing cost elements is determining final part cost.

Tipnis** has performed a cost comparison for the cost of a titanium alloy jet engine disk formed by several alternatives: conventional forging, isothermal forging, and HIP plus conventional hot forging. In Table 4-2, the costs for blank fabrication by each process are shown, including all operations up to the sonic inspection stage (done by a forging company). Table 4-3 shows the total manufacturing cost, which includes the blank, finished machining, and

---

*S. Shah and J. McKeough, Society of Manufacturing Engineers, MF83-908, Near Net Shapes-I Conference, Pittsburgh, September 1982.

**V. A. Tipnis et al, "Economic Models for Processing Alternatives: Part II Application to Ti6242 Alloy Compressor Disk," Experimental Verification of Process Models, edited by C. C. Chen, American Society for Metals, 1983.

Table 4-2

BLANK FABRICATION LEVEL COSTS FOR A Ti-6242Si DISK
(Lot Size of 50 Parts)

	C	H	I
Raw Material Cost ($/part)	950	1900	712.5
Tooling Cost ($/lot)	550	5000	5000
Processing Cost ($/part)	775.8	683.3	581.85
Consumable Cost ($/lot)	400	350	350
Total Cost ($/part)	1744.8	2690.3	1401.35

C = Conventional forging sequence.

H = HIP + forging sequence.

I = Isothermal forging sequence.

SOURCE: Isothermal and Hot-Die Forging of High-Temperature Alloys, MCIC-83-47, June 1983, Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio.

Table 4-3

MANUFACTURING LEVEL COSTS FOR A Ti-6242Si DISK
(Lot Size of 50 Parts)

	C	H	I
Blank Cost ($/part)	1744.8	2690.3	1401.35
Processing Cost ($/part)	2031.12	1554.22	1756.02
Consumable Cost ($/part)	300	200	200
Total Cost ($/part)	4075.92	4444.52	3357.37

C = Conventional forging sequence.

H = HIP + forging sequence.

I = Isothermal forging sequence.

SOURCE: Isothermal and Hot-Die Forging of High-Temperature Alloys, MCIC-83-47, June 1983, Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio.

inspection. Isothermal forging is the cheapest procedure overall and is considerably cheaper than conventional forging. The high cost of HIPing is due to the titanium powder input cost, which is much higher than that for normal forging stock.

In HIPing certain rotating jet engine parts such as disks, the cost savings are 25 percent of the present practice. The current process uses 360 input pounds of Waspaloy for forging; the first-generation HIP used 220 pounds of powder. The second-generation HIP would reduce this to 175 pounds to achieve sonic shape, and the long-range plan is to reach near net shape, starting with 110 pounds of powder, more than a threefold saving over current practice. Figure 4-2 shows both the current process and the HIP process with attendant materials usages for making a turbine engine shaft. A fourfold reduction in input material is obtained using HIPing. Other processes such as extrusion plus rolling plus welding have enabled a 46 percent saving in making jet engine cases. Figure 4-3 compares the cost of several processes, including HIPing, relative to conventional forging for a compressor wheel. It can be seen that as the number of steps is reduced, the cost per part is generally reduced. In another case, a rotary forging process for making compressor drive shafts has reduced input material by 50 percent.

Precision casting of parts can offer similar savings over isothermal forging, up to 50 percent in input material. The buy-to-fly ratio in directionally-solidified and single-crystal turbine buckets is now down to about 1.2 to 1.

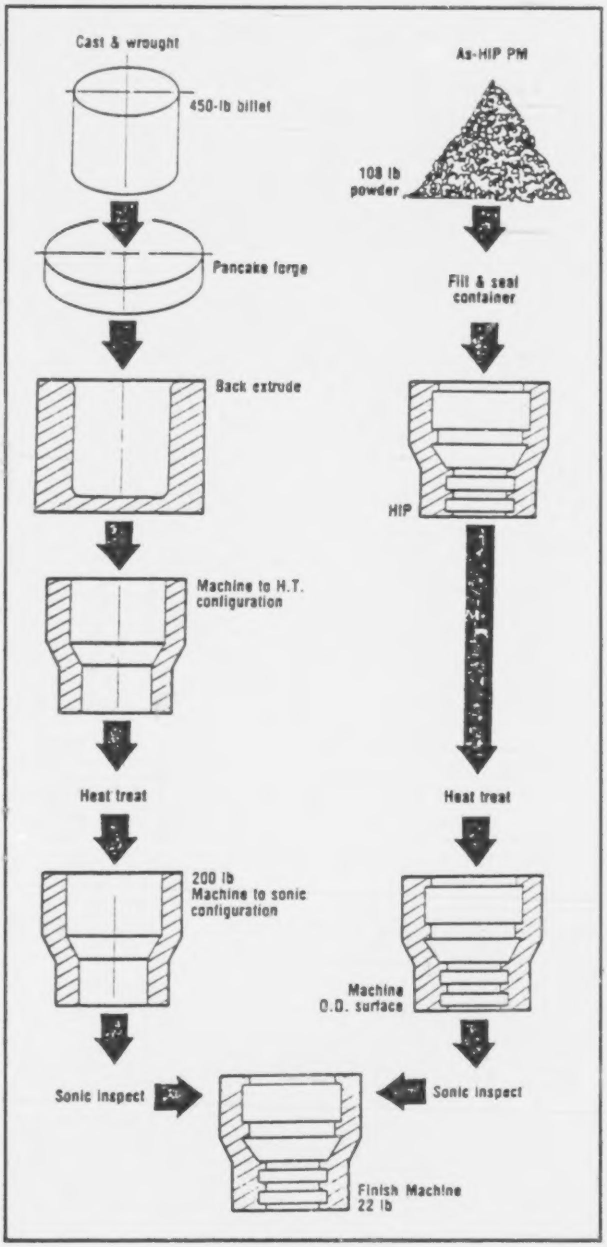
Automated forging allows forging rates up to 10 times faster than those achieved by conventional techniques. Although capital costs for automation equipment are high, the operating costs are significantly lower. Flashless forging technology (which eliminates the extra metal squeezed out around the sides of the die) can reduce machining costs by 30 to 100 percent.

VALUE OF POTENTIAL SAVINGS IN THE FORGING INDUSTRY

In 1979, a good year for the metals industry, the total value of forgings production in the United States was $2.61 billion, according to the Forging Industry Association, including $323.5 million for aircraft engines and engine parts and $675.65 million for total aerospace applications. A simple calculation based on some of the previous cost comparisons gives an idea of the potential savings possible using near net shape technologies. The Tipnis results indicated an 18 percent saving over conventional forgings for isothermal forgings. If isothermal forging and hot die forging were pervasive in the aerospace industry, a maximum of $122 million might theoretically be saved. Of course, these technologies will not be used to make every part, but this gives some idea of the maximum potential savings involved. In aircraft engines alone, savings similarly calculated are on the order of $58 million per year. In time, as more use is made of near net shape technology, further savings will accrue as an increasing fraction of the total $2.61 billion figure.

Figure 4–2

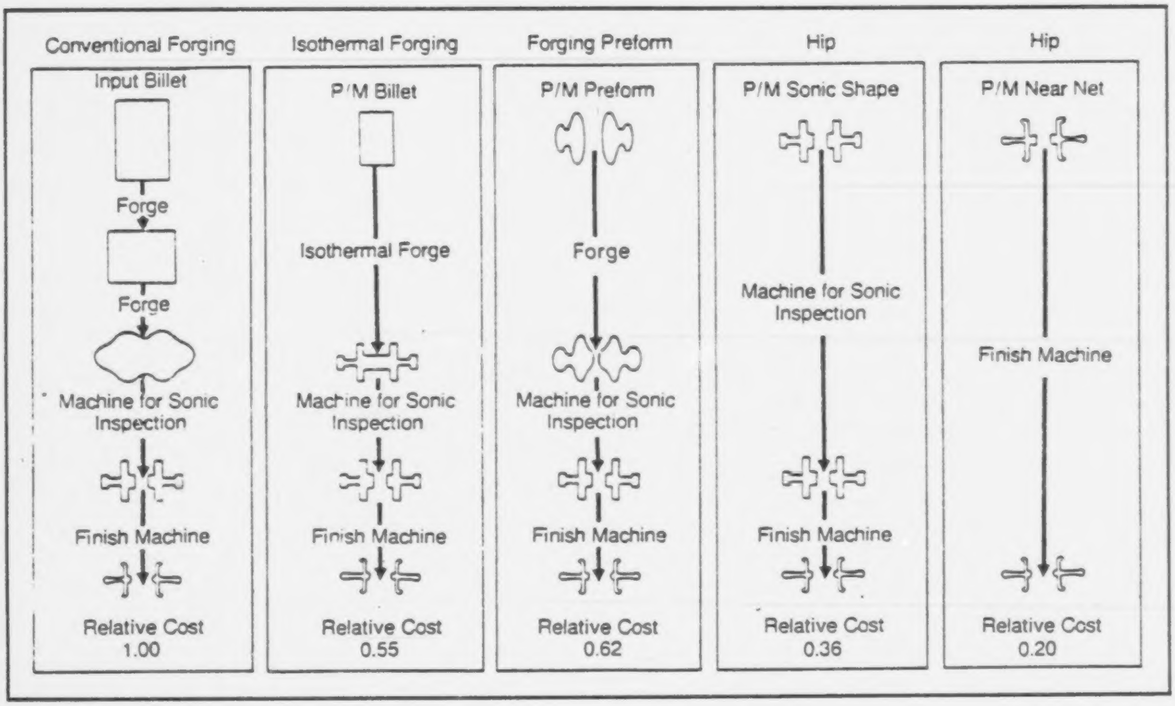
COMPARATIVE MANUFACTURING PROCESSES FOR MAKING A SUPERALLOY TURBINE ENGINE SHAFT


Cast & wrought
450-lb billet
Pancake forge
Back extrude
Machine to H.T. configuration
Heat treat
200 lb
Machine to sonic configuration
Sonic inspect
As-HIP PM
108 lb powder
Fill & seal container
HIP
Heat treat
Machine O.D. surface
Sonic inspect
Finish Machine
22 lb

SOURCE: *Production to Near Net Shape Source Book.* 1983. American Society for Metals. p. 243.

Figure 4–3

RELATIVE COSTS OF FORMING PROCESSES: HIP VERSUS FORGING FOR A COMPRESSOR WHEEL


Conventional Forging
Input Billet
Forge
Forge
Machine for Sonic Inspection
Finish Machine
Relative Cost 1.00
Isothermal Forging
P/M Billet
Isothermal Forge
Machine for Sonic Inspection
Finish Machine
Relative Cost 0.55
Forging Preform
P/M Preform
Forge
Machine for Sonic Inspection
Finish Machine
Relative Cost 0.62
Hip
P/M Sonic Shape
Machine for Sonic Inspection
Finish Machine
Relative Cost 0.36
Hip
P/M Near Net
Finish Machine
Relative Cost 0.20

SOURCE: *Iron Age*. February 23, 1981. p. 79.

MATERIALS COSTS VERSUS VALUE-ADDED COSTS

Parts experience a significant markup from the forging company to the aircraft or jet engine company. A forging is typically valued at twice the material cost and can be marked up 300 or 500 percent when it is finally put into the jet engine. A turbine blade casting has only a few dollars' worth of metal in it, but the yields are only 50 to 75 percent. The overall value of the final blade in the engine is typically as much as 500 times the value of the input material. Coatings on the blades run a factor of five times the materials cost. A typical 6000-pound jet engine might cost $3.5 million; the cost of materials in that engine at an average of $10 per pound of alloy is only $60,000. Any savings in materials costs are dwarfed by the added value to the parts. Materials conservation per se is therefore not an overriding issue with most manufacturers.

The most important driving force is cost reduction in parts fabrication; costs can be reduced by several routes:

- by overall fabrication cost reductions, e.g., in machining, energy input, fewer forging stages, and less input material;
- by lifetime extension of parts, e.g., HIPing used parts and castings, coatings, and surface modification; and
- by improved yield of parts and control of manufacture for better reproducibility.

The overall cost reductions in fabrication will vary depending on the part being produced. Lifetime extension will reduce maintenance costs as well as the need for spare parts. Coatings, particularly those using vacuum plasma spraying and ceramics, have extended operating life threefold in turbine engines.

INSTITUTIONAL BARRIERS

Nontechnical impediments exist to the advancement and greater utilization of the new technologies. Some of these are briefly outlined below.

The aerospace industry is very sophisticated when it comes to design. Designers of jet engines or aircraft tend to readily consider the use of new types of materials or parts fabricated by new technologies if properties and performance can be improved. Although this was stated by a major engine maker, a smaller company specializing in superplastic-forming and diffusion-bonding did mention that utilization of their products was being hindered by the conservation of designers who preferred to use castings because they were more familiar with them.

In the use of HIP, ASME codes of manufacturing have been slowing down the proliferation of HIP facilities in some states. Only in Massachusetts and Texas does the code not apply to the manufacture of vessels for HIP furnaces operating at pressures higher than the boiler range. Massachusetts apparently has not included HIP vessels under its code and Texas placed no code restriction on them at all. The ASME Code for high pressure vessels has been in effect for about 20 years. HIP vessels fall under the same code as most other vessels, particularly those for the nuclear industry. The code is designed to ensure adequate safety features in pressure vessel design and provides proper guidelines for production. The net effect of the codes is not to stop the building of HIPing facilities, but they do slow things down, since state inspectors must be brought in to check everything out and bureaucratic coordination may sometimes be difficult.

There are two important issues in scrap recycling. One of the most challenging problems confronting the fabricators is the inspection of parts requiring acid inspection. Acid handling and disposal is a major cost problem for the companies. The effort to comply with EPA regulations on acid disposal has led to a 30 to 40 percent increase in price for finished parts because of the high costs of disposal.

The other issue in scrap recycling relates to recovering metals from ECM and EDM sludges. Several companies have developed processes that appear technically feasible. However, without some government funding to encourage development through the pilot plant stage, these processes may not reach commercial development. The processes are not economical unless the costs of disposal are considered. Superfund money has been suggested as a potential source of development funds.

Certification of parts for aircraft has always taken a long time, but the process is required for their use in the aircraft. A period of 10 years is not unusual to qualify a new alloy or a new process like Gatorizing for commercial application. The criteria for performance and properties are becoming increasingly stringent. This is having the effect of eliminating smaller fabricating companies from the industry, ultimately leaving only the larger firms, which can keep their costs per part lower by virtue of their larger volume.

The fabricating industry is feeling the pinch from several sides now. The large engine manufacturers wish to cut their quality control costs by up to 50 percent and assign more responsibility for quality control to the forgers and casters. Forgers and casters will therefore be further pressed to quickly implement clean metal technology with advanced forging and casting processes in order to sharpen the quality and maintain cost control.

In addition, there are large quantities of nonaircraft forged products being imported into the United States from abroad. Eventually, these may include higher-quality aircraft products as well. A number of international partnerships have been formed, including Pratt and Whitney with Airbus, MTU and Fiat; General Electric with CFM and SNECMA; and Rolls Royce with the Japanese. All of these partnerships are involved with producing new designs of jet engines and they are bound to change the environment of the industry in an as yet unforeseen way. They could potentially lead to a decline in U.S. competitiveness in world markets for performance metal products.

To summarize, there still remains some degree of preference on the part of designers, particularly in nonaerospace uses, for materials made by technologies with which they are comfortable, although in aerospace there is a greater tendency to use new technologies because of the aggressive drive for higher performance and cost savings. Complying with EPA regulations on metal sludges and acid disposal is adding significantly to the cost of producing parts, but at the same time it is providing some incentive to develop recycling technology as a less-costly alternative to disposal. New competition from abroad in the form of imports and cooperative technology agreements, as well as more stringent quality controls, are strengthening the drive toward higher quality and lower fabrication costs. Computer-aided design is a technology that could assist designers in specifying new types of materials for applications; however, the problem is that designers tend not to want to be the first to use it.

SUMMARY OF RESEARCH AND DEVELOPMENT ACTIVITIES

A brief summary follows of important R&D activities carried out by government agencies, corporations, and universities.

The total Federal R&D budget for 1984 is projected at $47 billion, up by over $6.7 billion (17 percent) from FY 1983. The center of the materials technology thrust will be the new National Center for Advanced Materials, to be located at the Lawrence Berkeley Laboratory; however, the work at this center is expected to be oriented mainly toward physics.

The major centers of government-sponsored R&D in materials technology have been and will continue to be: the National Science Foundation (funding many university programs); the Department of Defense, working through the Air Force Materials Laboratory (Wright Patterson), the Army Research Office, and the Office of Naval Research; the National Bureau of Standards of the Department of Commerce; and NASA.

A brief listing of key programs oriented toward metals-processing technology is given below:

Agency	Budget FY 1984 ($ Million)	Research Areas
Department of Defense:	29,900	All programs
Air Force Office of Scientific Research	8-9	Structural materials for aerospace; large part devoted to powder metallurgy
	10-12	Manufacturing technology Near net shape HIPing improvement Weldability of superalloys Superplasticity Creep behavior of ODS alloys Modelling creep crack growth processes Modelling new manufacturing processes
Army Research Office	6.7	General metals and materials
Office of Naval Research	7.98	Welding, corrosion, and rapid solidification
National Science Foundation	1,292.3	All programs
	9.5	Metals-related
Department of Interior:	329	All programs
Bureau of Mines	12.4	All programs -- some metals fabrication
Department of Commerce:		
National Bureau of Standards	125	Rapid solidification (large emphasis), composites, and advanced processing
NASA	684	All programs
NASA-Lewis Research Center	N/A	Near net shape forging and casting technology, COSAM program for conserving critical metals

Major work on aircraft and jet engine part fabrication is carried on at the Air Force Wright Patterson Laboratory and at the NASA-Lewis Research Center. Part of NASA-Lewis' COSAM program (Conservation of Strategic Aerospace

Materials) will be devoted to new fabrication technology, but so far it has mainly been working on substitution (primarily of cobalt so far) through new alloy developments. This work will also be extended to other metals -- chromium, columbium, and tantalum.

Several research facilities conducted major pioneering work in the mid-1960s and early 1970s, with much of the work funded by the federal government. The Illinois Institute of Technology Research Institute (IITRI) performed important research on isothermal forging. The Battelle Columbus Research Lab has done and is still doing pathbreaking work on HIPing. IITRI and Battelle also continue to be involved in advancing near net shape technology.

Researchers at Wright Patterson have built detailed cost comparison models to evaluate new forging, machining, HIPing, and other near net shape processes. One of the key men involved left to found a firm, Tipnis Associates in Cincinnati, to pursue the modelling of advanced metals-manufacturing technologies.

UNIVERSITY PROGRAMS

There is a great amount of research being conducted through government funding. Important new centers are being formed -- the new center at Lawrence Berkeley Laboratory, for example. The Materials Processing Center at M.I.T. is a new kind of facility primarily funded through industrial sponsors to advance the state of the art in powder metallurgy, melting solidification, and rapid solidification technology.

Important work on ion implantation is being conducted by Professor Potter and associates at the University of Connecticut and by Professor Starke at the University of Virginia. Rensselaer Polytechnic Institute has long been involved in advancing powder metallurgy technology under Professor Lenel. Professor Duwez of CalTech was the pioneer in rapid solidification technology and is still carrying on this work. Professor Tien at the Center for Strategic Materials at Columbia University is one of the world's foremost authorities on superalloy melting and alloy development technology. Further information on university programs can be supplied by any of the recent superalloy, near net shape, or rapid solidification symposia, which present papers by authors from academia, government laboratories, and corporations.

CORPORATE R&D

Major research on new metals-processing technology has historically been and is still being done by the companies involved in the aerospace industry.

The jet engine manufacturers, Pratt and Whitney Aircraft, General Electric, and Garrett Turbine, have organized programs in all phases of near net shape fabrication. Pratt and Whitney has led in the commercialization of an isothermal forging process, Gatorizing, which it licenses to various component manufacturers. Pratt and Whitney has also pioneered in the development of directional solidification and single-crystal casting for turbine buckets, now incorporated in some of their engines, as well as in using powder preforms of high-performance alloys like IN-100 and MERL 76. General Electric has been oriented toward HIPed and forged high-performance powder alloys like RENE 95.

The major forging companies, such as Wyman Gordon, Ladish, and TRW, have licensed the isothermal forging and hot die forging processes, and supply parts to jet engine and aircraft builders. Their programs are largely oriented toward forging development and ways in which such processes could be applied to new alloys.

Much of the research being done at corporate labs is highly proprietary, but some activities have become known through publications.

Howmet Turbine Components Corporation, a leader in the industry, has been heavily involved in vacuum plasma coating technology (the CoCrAlY and NiCrAlY coatings), precision casting, HIPing of cast parts, and near net shape forging. Martin Marietta, a major supplier of high-performance superalloys in the Mar M series (cobalt- and nickel-base) is active in melting and casting technology. INCO and its Huntington Alloys subsidiary are major suppliers of superalloys to the aerospace and chemical industries. INCO has developed and marketed ODS-type alloys for use in turbine engine hardware. Cabot Corporation, Special Metals, and Teledyne Allvac are also major suppliers of alloy stock and mill products to the forgers and aerospace companies. Cabot is particularly active in developing chemical industry and oil country products that use thin, nickel-base Hastelloy materials. Chromalloy is the leading company doing work in rejuvenating used aircraft parts by HIPing.

Industrial Materials Technology Corporation is a leader in HIPing technology and is continually seeking to lower HIPing costs and expand applications. Crucible Specialty Steel is very active in HIP development and powder metallurgy, and has introduced new tool steels formed from metal powders. Kennametal has long been using HIPing for producing its cemented carbide tool bits and is now pursuing outside toll work. It has also been active in the HIPing of castings. Cameron Iron Works, a major oil country goods supplier in Houston, has bought a large HIPing facility and in the future will be more active in applying HIP to oil industry equipment.

Universal Cyclops, a major specialty steel and superalloy supplier, has undertaken a major effort in powder metallurgy for making mill products and for forging preforms, for which it has developed the CAP process, described earlier.

Dynamet Technology is pursuing the technology of cold isostatic pressing followed by sintering. It is inexpensive relative to HIP and can accommodate any kind of input powders, from ODS to RST. The firm is expected to commercialize the process for superalloys and stainless in the near future.

Ontario Corporation specializes in superplastic-forming and diffusion-bonding technology and will be expanding applications to new alloy systems and end uses. Rockwell Science Center of Rockwell International is also working on this technology for alloy IN718, along with most of the other near net shape technologies. Allison Turbine Division of General Motors is working on diffusion-bonding (potentially of Waspaloy) for turbine blades and combustors.

Precision Cast Parts Corporation is the current leader in the production of large castings for gas turbine engines and aircraft structural parts. The firm casts superalloys, stainless steels, and titanium alloys.

Airesearch Corporation is the world leader in supplying auxiliary power units (APUs) to the aircraft industry. It currently has at least 80 percent of the market for these small gas turbine engines, which supply power to an aircraft while on the ground. Since these engines run much hotter than jet engines, Airesearch has done a lot of work on thermal barrier coatings. Cast turbine disks, which are not used at all on jet engines, may be implemented in APUs. The APU may be the first commercial application of ceramic blades in a gas turbine engine; the safety factors are not as critical, since the APU only operates on the ground, and the ceramic can withstand much higher temperatures than superalloys.

In the area of coatings and claddings, some key companies are Texas Instruments (for thin-gauge materials) and Lukens Steel (thicker-gauge plate).

The steel companies all undertake R&D efforts, such as continuous casting, ladle refining, and external desulfurization, all aimed at improving production technology. The major desulfurization reagent suppliers, such as Airco, Remacor, and Dow Chemical, and the systems engineering companies, such as Rossborough and Vulcan Engineering, do development work on the desulfurization process, as do the steel companies. All of the major steel companies do research on coatings and fabrication but not typically in the areas mentioned earlier, which are the preserve of the companies that primarily serve aerospace markets.

5

PROJECTED USE OF NEW TECHNOLOGIES BY END USE

The developing metals-processing and fabrication technologies have great future potential to conserve input material and reduce energy consumption and costs per part. The new forging, casting, and powder metallurgy technologies open up new avenues for metallurgy and materials engineering, particularly for the utilization of new alloys that previously could not be employed commercially because of insurmountable difficulties surrounding their fabrication into useful parts.

For example, isothermal forging is being applied because its use can enable the employment of new alloys. The process itself is more involved than conventional forging; the set-up times are longer, the proper inert atmosphere around the die must be maintained, and there must be proper die lubrication at very high temperatures. The process needs more controls because it involves forging to closer tolerances than conventional forging. Certain superalloys, such as IN-100, MERL 76, RENE 95, and Astroloy, are among the highest-strength superalloys available, but it is impossible to achieve optimum properties from these alloys by conventional means. IN-100, in particular, is too brittle in conventional wrought alloy form to be further forged and machined into the turbine disks that are desired. However, the alloy shows superplastic behavior within a certain temperature regime that can be exploited by isothermal forging, or Gatorizing. Gatorizing is performed on only the above-mentioned alloys today; Astroloy is in process of being phased out commercially, since it is an earlier-generation alloy. Popular alloys IN 718 and Waspaloy are not Gatorized because they do not exhibit the desired superplasticity. However, the Gatorizing process has enabled the cost-effective exploitation of superior properties in IN-100 and other alloys in a critical turbine engine component.

The potential exists for new and complex alloys to be exploited in commercial components because of the ability of near net shape technologies to fabricate them economically. In addition, these technologies are producing more reliable parts than were produced with conventional cast/wrought technology (for example, RENE 95 powder metallurgy alloys are now successful, following some initial unreliability problems in parts).

PROJECTIONS OF FUTURE IMPACTS

The outlook for the use of new technologies can be expressed in terms of the future expected effect on conservation of critical metals. Data that indicate exactly how much chromium and cobalt go into forgings, castings, and powder metallurgy applications are not available, nor is there quantitative information on the amount of material involved in isothermal forging operations, precision casting, or HIPing. Using the best available information, we have developed a table by end use and technology that indicates the estimated degree of potential percentage savings in process yields in the use of chromium and cobalt over 10-year and 25-year time horizons (see Table 5-1). These savings represent incremental savings from today's base levels and are for input material. Net savings would be smaller, after allowance for recycling.

These conservation figures are judgmental estimates based on industry contacts at major corporations involved with the technology and the engineering literature. It should be noted that the impact of the technologies on gas turbines applies to both chromium and cobalt, since both are contained in the engines. In oil country tubular goods applications, the estimates apply to chromium, since little or no cobalt is used in the alloys for this application. In constructional steel, the impact is primarily on manganese. Other end uses in which savings are possible include such potential applications as automotive and off-highway vehicles, chemical processing, pulp and paper production, machinery, industrial equipment and tools, electrical equipment, power plants, and ordnance and military equipment.

The three major factors leading to savings are: net shape technology savings in input material; lifetime extension; and redesign of parts based on property improvements available from processing changes. The ranges shown in the table are for input alloy material from the melters for the application. This is particularly important for gas turbines since the issue is complicated by the way cobalt and chromium consumption may be defined. The numbers usually published represent consumption by the melters, who produce alloy stock and mill products that are then shipped to fabricators; these numbers do not represent consumption in the final parts themselves.

In gas turbines, the expected impacts on conservation and cost savings should be substantial over the next 10 years and particularly during the next 25 years. It is felt by industry sources that over these time frames, the technologies now employed will still be in use, since it typically takes 10 years to develop and qualify new alloys, and the time interval between

Table 5-1

FUTURE SAVINGS OF CHROMIUM, COBALT, AND MANGANESE FROM THE USE OF NEW FABRICATION TECHNOLOGY, FOR 10-YEAR AND 25-YEAR PROCESSES
(Percent)

End Uses	Melting & Refining		Forging		Casting		HIP		Surface Modifications and/or Cladding	
	10-Yr	25-Yr	10-Yr	25-Yr	10-Yr	25-Yr	10-Yr	25-Yr	10-Yr	25-Yr
Gas Turbines*	0-5	5-10	5-10	10-25	10-25	25+	10-25	25+	0-5	0-5
Oil Country**	0-5	0-5	0-5	0-5	5-10	10-25	0-5	0-5	10-25	25+
Construction Steel+	5-10	25+	0-5	0-5	5-10	10-25	0-5	0-5	10-25	10-25
Others++	5-10	5-10	0-5	5-10	10-25	25+	0-5	5-10	5-10	25+

NOTE: The savings shown in this table are reductions in input material from the smelters for each application.

* For Cr and Co.
**For Cr only.
+ For Mn only.
++For Cr, Co, and Mn.

SOURCE: Charles River Associates estimates, September 1983.

successive generations of jet engines is about 5 or 10 years. The industry is just now gaining some commercial experience with technologies that were on the drawing boards at least 10 or 20 years ago.

In oil country tubular goods applications for deep wells, the impact of casting and cladding will be most important, since tubing is usually not forged or HIPed, and melting and refining have a small impact on chromium utilization.

In constructional steel, the potential savings in manganese could become significant, particularly in the melting and refining processes for ironmaking and steelmaking previously described in Chapter 3. A 30 percent reduction in manganese demand could occur in the short term (10 years), and almost a 40 percent reduction could result in the long term (25 years).

Developments in technology are moving faster today than they were 10 or 20 years ago. There are so many different variations and avenues being followed that it is very difficult to predict the future course of events.

It is expected that R&D efforts will be focused on melting and refining to make cleaner metal. Emphasis will be placed on improving nondestructive testing of parts and on extending the lifetime of parts in service. Surface modification, coating, and cladding could increase dramatically in the future, with many kinds of alternatives available for every kind of application and environment.

The reduction of nontechnical institutional barriers will definitely expedite the expansion and diffusion of technology. In the area of codes and standards, the trend is toward greater performance and stringency in standards for properties of alloys and finished components. This is in keeping with the continued drive for increased performance per pound of material at the lowest cost, particularly in the aerospace industry. However, the removal of institutional barriers occurs more slowly than the removal of technical barriers.

Inevitably, it is expected that with the success of these new technologies in the aerospace industry, engineers in other fields will explore their applicability in nonaerospace uses.

Scrap recycling capability should increase in the future. However, the estimated potential savings shown in Table 5-1 assume no change from the present degree of scrap recycling. This question is left for another study to examine. However, as recycling capability progresses and as more of this material is reclaimed for critical metals recovery, scrap will potentially contribute as much if not more to the conservation of critical metals as do new processing technologies. However, not all scrap will be recycled, due to several factors: the need to properly identify scrap according to alloy type, difficulties in segregating scrap as parts become more complex due to coatings and multiple alloy construction, and the presence of such undesirable elements as hafnium.

6

THE STATUS OF UNITED STATES VERSUS FOREIGN TECHNOLOGY

The United States has always been the leader in advanced fabrication technology because it has traditionally been the most active in aerospace activities.

The United States currently has recognized superiority in advanced near net shape forging, such as isothermal (Gatorizing) and hot die forging, and in precision castings of large parts, as well as in directional solidification and single-crystal casting.

Rolls Royce, the major European jet engine builder, has been very innovative in materials technology but has been lagging in its application. The firm pioneered turbine blade air cooling technology, but General Electric and Pratt and Whitney are the leaders today in applying it. Rolls Royce has reportedly developed a new type of directional solidification technology to rival that of Pratt and Whitney.

In HIP technology, the United States is currently the leader in processing, but lags behind Europe in systems engineering. ASEA in Sweden is the leader in scaling up the HIPing process for large commercial-part production. The company's furnaces are currently recognized as the best available in the world.

In alloy-melting technology, U.S. companies have the edge in vacuum induction melting, vacuum arc remelting, electron beam melting, and VADER. However, the U.S.S.R. leads the United States in the application of electron beam remelting, and plasma-arc remelting technologies.

In superplastic-forming and diffusion-bonding, the United States is still the leader in the basic technology; however, much is being done in the United Kingdom for commercial jet engine applications. The United Kingdom may even be ahead of the United States in applying the technology. The U.S.S.R is also becoming interested in the superplastic high-carbon steels developed by Professor Oleg Sherby of Stanford University.

In ion implantation, major pioneering work has been done in the United Kingdom, which currently leads the United States in this area, although substantial research is now being conducted in this country.

Other countries are becoming more prominent outside the aerospace high-performance materials area. The Japanese appear to have some lead on the United States in cladding, particularly in superalloy clad steel tubing. Through their new materials-oriented research and development programs, the Japanese desire to become leaders in superalloy technology. This is evidenced by Nippon Steel's unsuccessful attempt to buy Special Metals Corporation, a leading superalloy producer in the United States. The buyout was disallowed by the Department of Defense on the grounds that Special Metals was involved in supplying the U.S. defense industry.

The Japanese have developed clad tubing for deep sour gas wells that is cheaper than the solid superalloy tubing supplied by American companies. Nyby of Sweden and VDM of West Germany are winning a considerable share of the chemical and oil industry markets for high-performance nickel-base and iron-base alloys.

With regard to basic steel production, the Japanese, the West Germans, and the Swedes tend to be the most innovative in steelmaking practices and in developing new technology. The West Germans were pioneers in developing external desulfurization, and the Japanese have applied it much more widely and effectively than have United States mills. The Japanese generally produce tonnage steel routinely, with far lower sulfur contents than are generated by U.S. producers. The West Germans and Japanese dominate the market for high-quality, very low-sulfur content large-diameter oil and gas transmission pipe. The West Germans also lead in the shape welding of steel products like boilers and other vessels.

Overall, the United States has established leadership in R&D, and no change is conceivable in the short term. However, in the long term, some U.S. companies are concerned about the future availability of a sufficient number of highly-trained engineers to maintain the United States at the cutting edge of technology. For example, Japan is currently graduating 30 percent more engineers than the United States.